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Survey of the Thermal Threat of Nuclear Weapons

Jack C. Rogers and T. Miller

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SURVEY OF THE THERMAL THREAT OF NUCLEAR WEAPONS

Prepared for:

OFFICE OF CIVIL DEFENSE
DEPARTMENT OF DEFENSE
WASHINGTON 25, D.C.

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By: Jack C. Rogers and T. Miller

SRI Project No. IMU-4021

Approved:

Robert A. Harker

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MANAGEMENT SCIENCES DIVISION

OCD REVIEW NOTICE

This report represents the authors' views, which in general are in harmony with the technical criteria of the Office of Civil Defense. However, a preliminary evaluation by OCD indicates the need for further evaluation of the fire threat of nuclear weapons and formulation of promising research and action programs.

ABSTRACT

This paper reviews the current state of knowledge on the thermal effects of nuclear weapons, atmospheric transmissivity, ignition of target elements, and fire propagation and spread. Some of the topics considered are:

- Importance of attack assumptions (delivery capabilities of the enemy, warhead types and yields, altitude of detonation, timing, and warning) in determining the characteristics of thermal radiation and the susceptibility of targets to thermal damage.
- Modification of the thermal radiation by the atmosphere, intervening cloud layers or other meteorological features, and target elements, such as trees and topography.
- Interaction of blast, radioactivity, and thermal radiation phenomena.
- Response of target elements to direct thermal radiation.
- Effects of weather and topography on target vulnerability and fire spread.
- Fire development and spread in target areas.
- Vulnerability of humans.
- Countermeasures.

This version of the report has been declassified to allow wider usage of much of the unclassified material contained in the original. As a consequence, certain figures and tables, as well as portions of the text, have been deleted.

FOREWORD

To understand the mechanisms of fire and their implications to civil defense in case of a nuclear attack, the Office of Civil Defense has instigated a broad range of research projects. In addition to this effort, considerable work is being sponsored by other government agencies, such as the Defense Atomic Support Agency, the National Bureau of Standards, the Department of Agriculture, and civilian groups engaged in the study of peacetime prevention and control of urban and wildland fires.

As an aid to the synthesis of the many data available and continuously being generated, Stanford Research Institute was asked by the Office of Civil Defense to "review the current state of knowledge on thermal effects of nuclear weapons, atmospheric transmissivity, ignition of target materials, and fire propagation and spread; evaluate the fire potential of large-yield detonations under a variety of assumed attack conditions with emphasis on the influence of cloud cover, rain, snow, terrain, and other climatic and geographic factors; and recommend promising research and action programs."

The present report reviews the broad aspects of the damage which might occur from thermal radiation in case of a nuclear attack on the United States. The report, together with four others, is submitted in fulfillment of the contract work statement. The other reports are:

A Preliminary Evaluation of Fire Hazards from Nuclear Detonations, an initial overview outline and discussion of the thermal effect of nuclear explosions and the resulting fire hazards (Miller, 1962).

Radiative Energy Transfer from Nuclear Detonations above 50-km Altitude, a technical investigation of the thermal effects of high yield weapons detonated at extremely high altitudes in clear atmosphere (Miller and Passell, 1963).

Transmission of Thermal Energy from Nuclear Detonations above 50-km Altitude by the Earth's Atmosphere, a survey of the literature and evaluation of the energy transmitted through a real atmosphere from very high altitude nuclear explosions. Recommendations for promising research are made (Passell, 1963).

Ignition of Materials by Large Yield Nuclear Weapons for Various Burst Heights and Atmospheric Conditions, a summary of the current state of knowledge concerning the range at which ignition of materials is expected to take place for various burst heights and atmospheric conditions. Areas are pointed out in which research programs are particularly needed for a thorough understanding of the range of ignition of materials under realistic conditions (Rogers, 1963).

This study was conducted in the Management Sciences Division of Stanford Research Institute for the Office of Civil Defense under contract OCD-OS-62-135, Task III.

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I INTRODUCTION

The Significance of Fire in World War II

It is generally acknowledged that fire was the major cause of destruction during World War II. In Germany, fire caused approximately 80 percent of the total structural damage to cities attacked by airborne weapons; the 54 principal cities had a median of 40 percent destruction, most of which was caused by fire. The percentage of total fire damage in England was similar. Ton for ton, incendiary bombs were five times as effective in causing damage as were high explosive weapons; see Bond, 1946.

In Japan, over 99 percent of the total bomb loads dropped on urban areas were of the incendiary type (as compared to 50-50 loads of incendiaries and high explosives dropped on Germany). As a result, 67 Japanese cities experienced a median of 48 percent destruction. It is impossible to comprehend the meaning of these figures and the associated mass loss of life without having seen the destruction or at least having read some of the detailed literature based on the World War II experience. The reader is referred to Fire Effects of Bombing Attacks (1959), Bond (1946), and Effects of Incendiary Bomb Attacks on Japan (1947) for accounts of these incendiary raids.

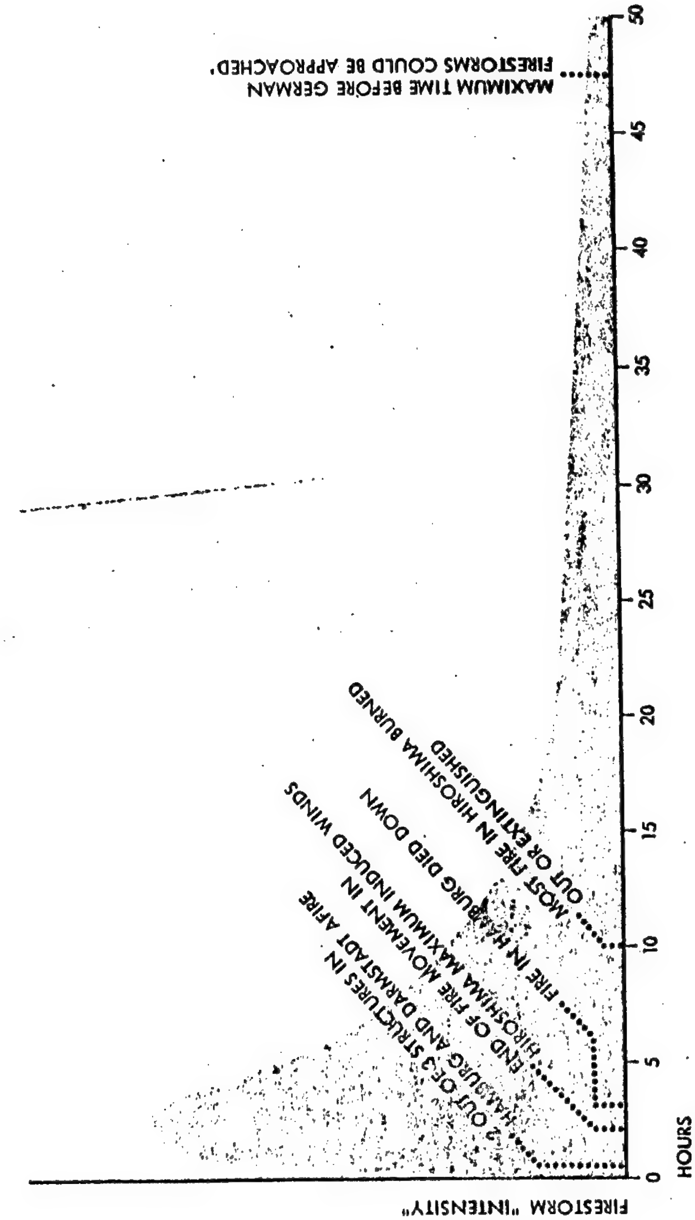
Extensive fires such as those experienced during World War II are commonly called mass fires. The mass fire may take the form of either a firestorm or a conflagration, depending on the natural wind conditions and topography, the number of ignitions per unit area, or other factors. The firestorm is an intense stationary fire; the conflagration is a moving fire of lesser intensity. Whereas the firestorm destroys practically everything aboveground, the conflagration is less destructive but can cover much larger areas. Figure 1 indicates the time sequence of the qualitative development of a firestorm. Figure 2 presents data concerning the magnitude of certain representative mass fires.

Fire Research since World War II

Recognizing the importance of incendiary effects in air raids, the Allies devoted considerable research effort during the war to the parameters

Figure 1

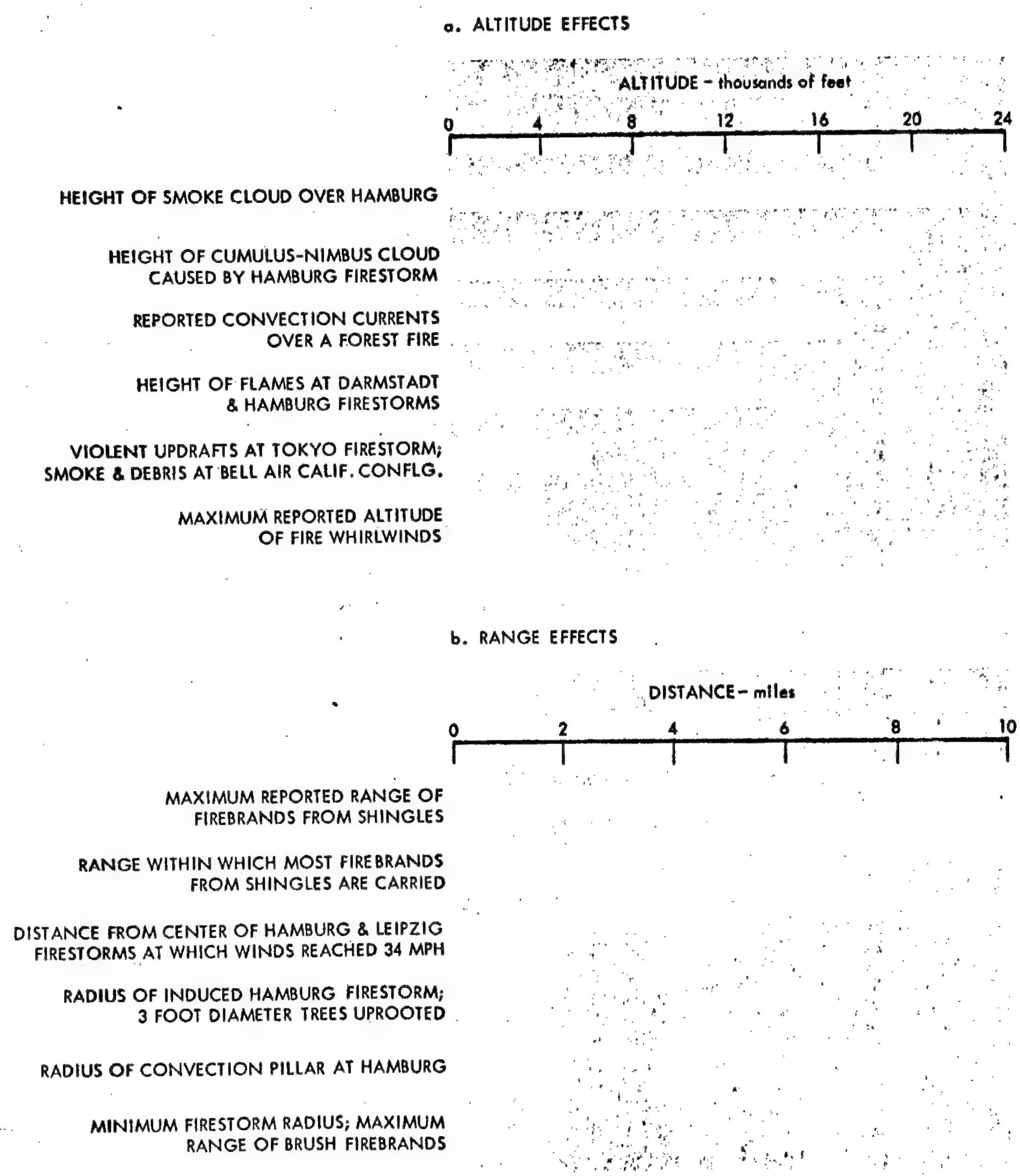
QUALITATIVE TIME BEHAVIOR OF FIRESTORMS



SOURCES: Bond (1946), Fire Effects of Bombing Attacks (1959)

Figure 2

SCALE OF REPRESENTATIVE MASS FIRES



SOURCES: Bond (1946), Fire Effects of Bombing Attacks (1959) and Wilson (1962)

affecting mass fire development. Studies were undertaken on the degree of "built-upness" of both Axis and English cities, the percentage of destruction as a function of bomb types and other variables, the effectiveness of both active and passive countermeasures, the rate of fire spread and fire development, and many other factors.

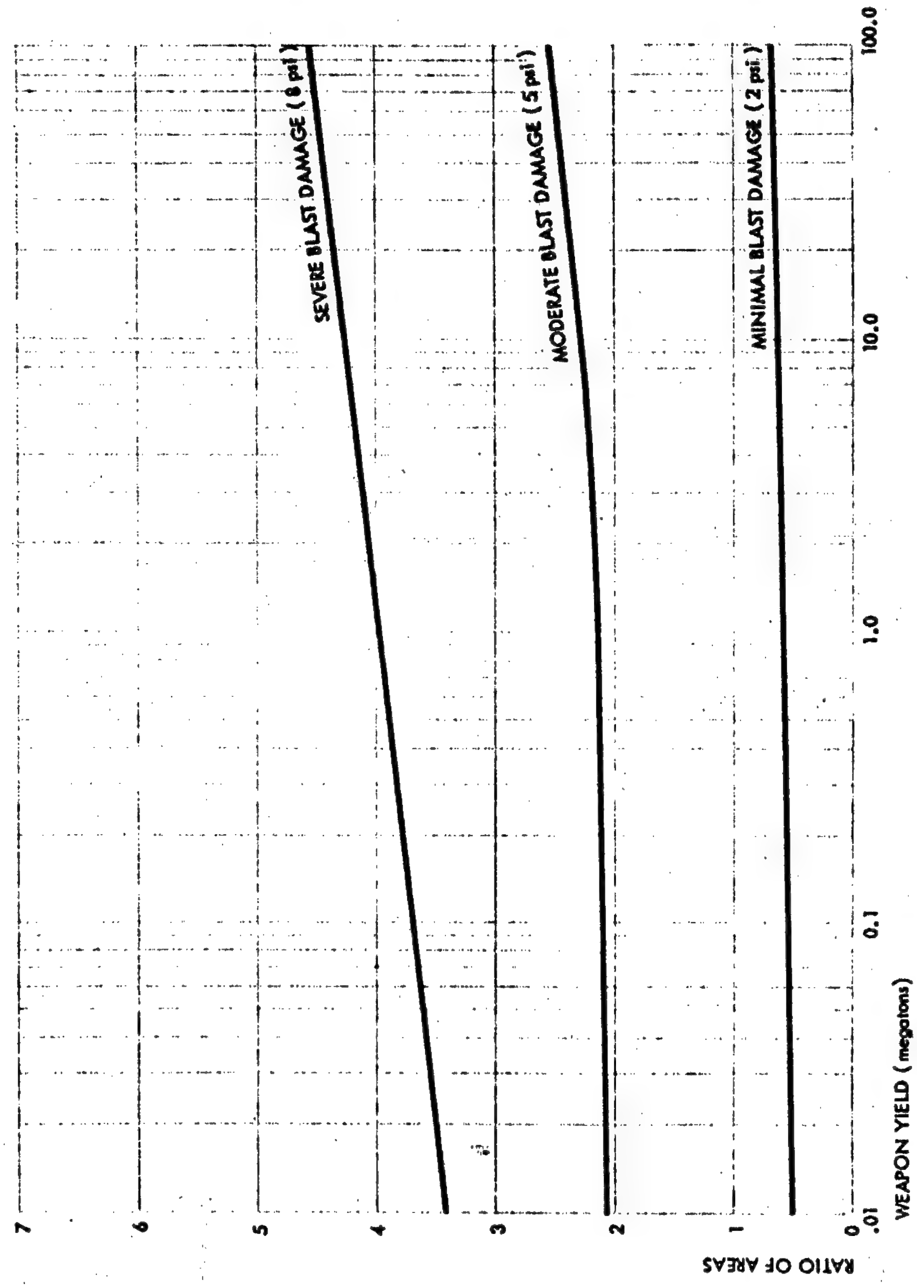
After World War II, the research emphasis was shifted from fire to blast and the effects of radioactivity. This shift of emphasis probably occurred for several reasons. First analyses showed that the area of blast damage from the nominal atomic weapons was as extensive as damage due to fires from incendiaries (see Figures B-1 and B-2). To the military planner, blast effects were far more predictable than fire effects for causing a required amount of damage. Perhaps more important, however, is the fact that studies on mass fire behavior are extremely difficult to formulate and test. This is principally due to the immense number of variables, the stochastic nature of fires, the complexity of even the simplest burning process, and the difficulty in scaling information derived from manageable laboratory or field experiments to apply to large scale mass fires. Ignition of materials and, in some cases, ignition of structures could be studied in the atomic tests which followed World War II. The tests, however, could not be instrumented in any feasible manner for the investigation of mass fires although they were successful in supplying quantities of data on blast and radioactive fallout.

In recent years, there has been a renewed interest in the study of fires and other thermal damage from nuclear weapons, occasioned in part by the development of thermonuclear weapons. With these high yield weapons, the area in which ignitions could occur is larger than the area of blast damage (under ideal weather conditions). Figure 3 shows the ratio of the area within which a typical kindling fuel (newspaper) would ignite to the area affected by blast damage for several levels of overpressure.

Recent tests by the Soviet Union of extremely large yield weapons and the acknowledged superiority of Soviet missiles in lifting heavy payloads to any desired altitude and range have added impetus to the study of fires produced by nuclear attacks.

An additional stimulus to fire research has been the extreme difference of opinion on the importance of fires resulting from nuclear attacks. Dr. Harrison Brown stated that "very large bombs (about 1,000 megatons) will be built which, when exploded at an altitude of about 300 miles, could sear six western states"; see Brown and Real (1960). In contrast, Dr. Jerald E. Hill, in his report to the Committee on Government Operations, claimed that "the damage resulting from fire will be rather of a third order effect compared to the potential damage from blast and

Figure 3
RATIO OF FIRE AREAS TO BLAST AREAS



SOURCES: Based on Martin (1959) and Glasstone (1962)

radiation effects"; see "Civil Defense . . . 1961." The basic reason for these differences of opinion is that the mechanisms of fire and many of the thermal effects of nuclear weapons are still unknown.

Interest in the fire potential of nuclear weapons has also been generated by the increased recognition that adequate shelters--and possibly other countermeasures--can afford considerable protection for the population even in the extreme conditions of a firestorm. In the Hamburg firestorm, for example, carefully documented reports show that the principal reason that fatalities among the total population were limited to 14 percent was that 79 percent of the people had access to some form of shelter from fires. In fact, not a single casualty was reported in 19 percent of the population that sought shelter in bunkers* and splinterproof** bomb shelters (Earp, 1953).

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* Bunkers--shelters characterized by heavy, reinforced concrete construction, many rooms or compartments, large capacity, completeness of utilities, and facilities for air treatment and control. All bunkers had air conditioning systems which provided for ventilation, heating, and, in some cases, cooling. The fresh air intakes were usually located well above the ground in outside walls. See Earp (1953).

** Splinterproof shelters--shelters consisting of single-story structures, standing clear of other buildings, and holding up to 500 people. Construction included an air-lock at the entrance and presumably a ventilating system although no details of the latter are known. See Earp (1953).

II SUMMARY

The purpose of this paper is to review the current state of knowledge on the thermal effects of nuclear weapons, atmospheric transmissivity, ignition of target materials, and fire propagation and spread. As a guideline in establishing the scope of the study, two important goals are assumed for the Office of Civil Defense in fire research. These are (1) to evaluate the ultimate damage to property and population which would be expected from thermal radiation if the United States be attacked with nuclear weapons and (2) to compare these results with the damage expected if feasible countermeasures be taken. Keyed to these goals, the review follows more or less the sequence of events which would occur following an assumed attack.

The Effect of Attack Assumptions on Thermal Damage Estimates (Appendixes A and F)

The assumptions made concerning the tactics employed by an enemy in an attack influence two main inputs to thermal damage estimates. These are (1) the characteristics of the thermal radiation, viz., the rate of delivery and the intensity of the thermal energy, and (2) the susceptibility (or vulnerability) of the target elements. No literature source has been found which specifically considers the implications of the attack assumptions on the thermal radiation damage to be expected. For this reason, these assumptions are discussed rather thoroughly in Appendixes A and F of this report.

Attack Assumptions Affecting Thermal Radiation Characteristics

Delivery Vehicle Capabilities

Classified paragraph pertaining to delivery vehicle capabilities has been deleted.

Assumptions concerning the accuracy of the Soviet missiles are probably not critical to the problem since, compared to the large radii of weapon effects, the aiming errors would be small.

The possibility that the Soviets could launch a salvo of missiles (that is, a number of missiles arriving on the same target at essentially the same time) poses a particularly serious threat from the standpoint of thermal radiation. A cursory examination in this paper indicates that (1) for megaton yields, the long thermal pulses would possibly overlap, creating a higher intensity of radiation on any given target than would be created by missiles fired independently; (2) fires created by separated ground zeros within a target area could coalesce intc mass fires; and (3) a salvo of missiles would be relatively less vulnerable to proposed AICBM terminal defense systems.

For the nonsalvo, multiple weapon case, the vulnerability of some target elements would increase for the follow-on weapons. For example, more than twice as much thermal energy is required to char a white painted wood surface than is necessary to ignite a charred one. For other targets, such as persons who have taken shelter after the first detonation, the vulnerability might decrease. From the literature review, it appears that no effort has been directed to the evaluation of thermal damage for the realistic case of more than one weapon on target.

Types of Warheads

Two classified paragraphs on multiple warhead deleted.

Special warheads might be developed which would create a reflecting layer above the detonation altitude to magnify the thermal effects to the ground. No analysis has been made of this possibility.

Choice of Yield

Increasing the yield of a weapon not only increases the total thermal energy emitted but lengthens the time of energy delivery. This implies that for the same materials, the larger the yield, the more total calories would be required for ignition. This important fact is often overlooked; see Figure 4.

Classified paragraph discussing differences in the thermal pulse shape between classified and unclassified literature has been deleted.

Altitude of Detonation

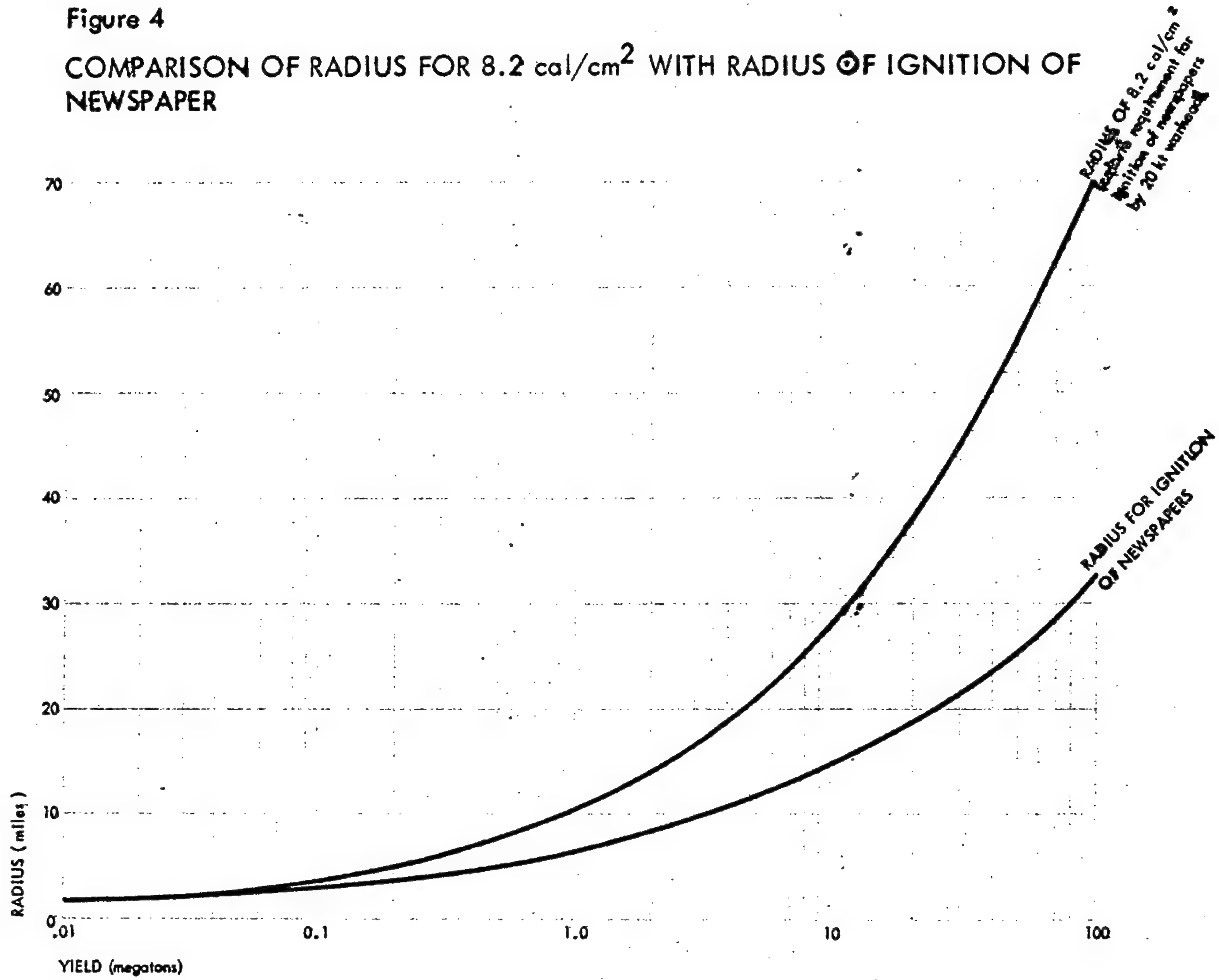
The enemy has the choice of any altitude of attack from ground level to outer space. The choice significantly affects the rate at which thermal radiation is emitted from the weapon, as well as the total thermal energy per unit of area reaching the ground. For ground bursts, a method is developed in Appendix A and F to relate the thermal pulse shape to that of a low altitude air burst. Similarly, based on the results of Miller and Passell (1953), methods are presented which relate both the pulse shapes of a very high air burst (above 50 km--31 miles) and an outer space burst (above 83 km--52 miles) to low altitude air bursts.

Classified paragraph on the thermal pulse shape has been deleted.

Based on these results, the ultimate effect of the altitude variation on the ranges at which materials will ignite is considered in detail by Rogers (1963).

Figure 4

COMPARISON OF RADIUS FOR 8.2 cal/cm^2 WITH RADIUS OF IGNITION OF NEWSPAPER



SOURCES: Based on Martin (1959) and Glasstone (1962)

Attack Assumptions Affecting the Vulnerability of Targets

Two main assumptions concerning the attack can affect the target vulnerability--the time of the attack and the amount of warning which the United States would have.

Timing of the Attack

In evaluating fire potential from nuclear weapons, the time (year, season, hour) of the attack is particularly important since (1) the year determines the technology of attack and defense; (2) the season alters the susceptibility of a particular target area to fire although the fire season differs radically in different areas of the United States; and (3) the hour of the day influences wind speed and direction, atmospheric transmission, location of target population, probability of cloud cover, and several other important factors. A literature review of these effects is presented in Appendix A.

Classified paragraph on the effect of time on countermeasures has been deleted.

Warning

Two classified paragraphs pertaining to warning have been deleted.

No information has been found on the quantitative importance of warning to fire fightingunits in alerting personnel, readying equipment, and making emergency preparations to fight mass fires.

Interaction of the Direct Thermal Radiation with the Atmosphere, the Target, and Other Weapon Phenomena (Appendix B)

Once the tactics of the attack have been specified, the weapon phenomena in most cases are determined, as discussed above. After a nuclear detonation, the thermal radiation from the fireball would be (1) attenuated by the atmosphere; (2) modified by intervening cloud layers or other weather features; and (3) screened or reflected by topography, trees, windows, and other elements in the target area. When the thermal radiation, which has been modified by the environment, strikes susceptible targets on the ground, ignitions, as well as skin and retinal burns in human beings, may occur over a wide area. There may also be important interactions of the thermal radiation with the blast and radiological phenomena of the weapon. These topics, which are considered in Appendix B, are summarized below.

Modification of the Thermal Radiation by the Atmosphere, Clouds, and Topography

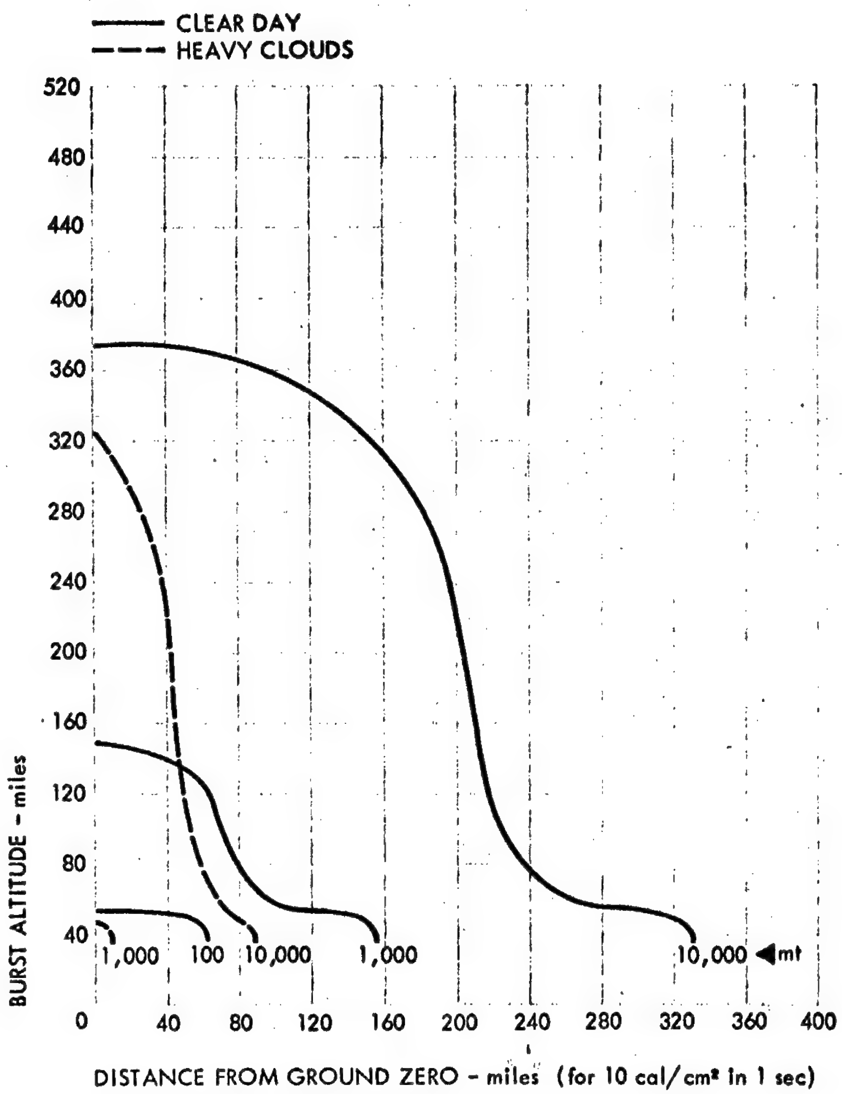
It has been found that the amount of thermal energy which the atmosphere will transmit can vary from almost zero to nearly 100 percent, depending on weather conditions. Reflections from cloud and snow can increase the energy arriving at the target still further.

Recent analyses of high altitude and above-the-atmosphere bursts are summarized in Figure 5. Note that the radius at which 10 cal/cm^2 (in one second) is received from a 10,000-mt burst at 45 miles altitude can vary from 80 to 325 miles, depending on weather conditions. Note also that only bursts larger than 10,000 mt would be a threat at orbital altitudes. The relationship of these thermal radii to the radii at which materials will burn is summarized in Rogers (1963).

The most complete analyses of atmospheric transmission have been made on the effects of variations in visibility. The effects of cloud layers

Figure 5

THERMAL RADIUS FOR HIGH YIELD, HIGH ALTITUDE BURST (receiver oriented for maximum thermal radiation)



SOURCE: Based on Passell (1963)

were derived from solar transmission data for bursts above the clouds, and analytic approximations were developed for bursts below cloud layers. Little information is available concerning bursts within clouds, between layers of clouds, in broken clouds, or in the presence of precipitation. In addition, the direct effects of a nuclear detonation on clouds and fog are unknown, for most cases of interest.

A summary of some of the results on the modification of thermal radiation by atmospheric transmission and meteorological condition is shown in Figures 6 and 7. As indicated, the ignition radius of dry pine needles (and of colored fabrics) can vary from less than one mile to as much as 20 miles. It should be noted that, due to differences in estimates of material response to thermal radiation, these curves may apply to 10 mt weapons or to weapons as large as 35 mt. This is discussed in detail in Rogers (1963).

No studies have been found in this review which analytically or statistically consider the importance of topography in shielding a target area from the thermal radiation from a nuclear weapon. (Such studies are commonplace in the study of airborne and ground-based radar line-of-sight.) The shielding afforded by the topography would be greatest for low altitude bursts, of course, but would be of little effect in a heavy fog when a maximum diffusion of the thermal energy would take place.

Interaction of the Thermal Pulse with the Target Complex

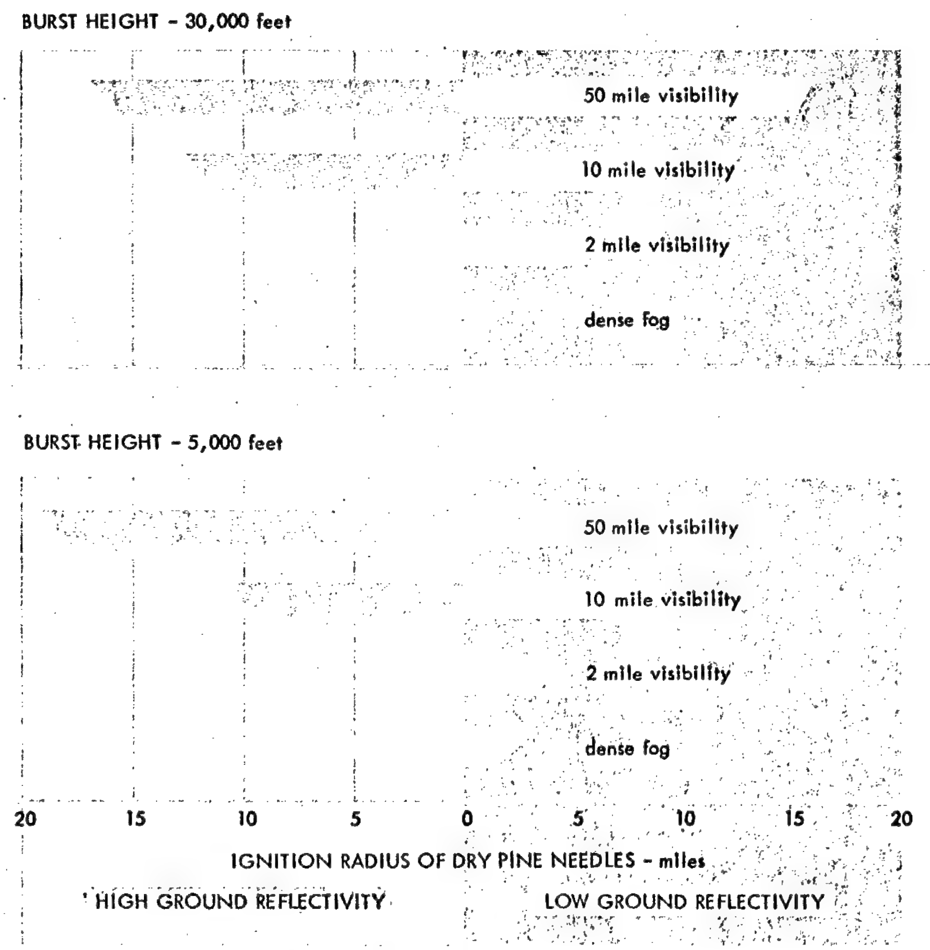
Response of Materials to the Thermal Pulse

Extensive laboratory tests have been completed at the Naval Radiological Defense Laboratory and elsewhere to determine the reaction of kindling fuels* to direct radiation from simulated nuclear thermal sources. Unfortunately, the laboratory work at NRDL does not agree too well with the results given in The Effects of Nuclear Weapons, which presumably is based both on field and laboratory data. Using the NRDL data and assuming very clear weather, the radii of ignition of materials must be increased by 70 percent or more (depending on the materials under consideration) to agree with the derivations based on the ENW. For periods of low visibility, the differences are less exaggerated. This problem is discussed in the summary report, Rogers (1963).

* Thin material of the order of 0.01 inches thick or low density materials, such as rotted wood.

Figure 6

IGNITION RADIUS OF DRY PINE NEEDLES FOR CLOUDLESS DAY
(optimally oriented receiver, real atmosphere)

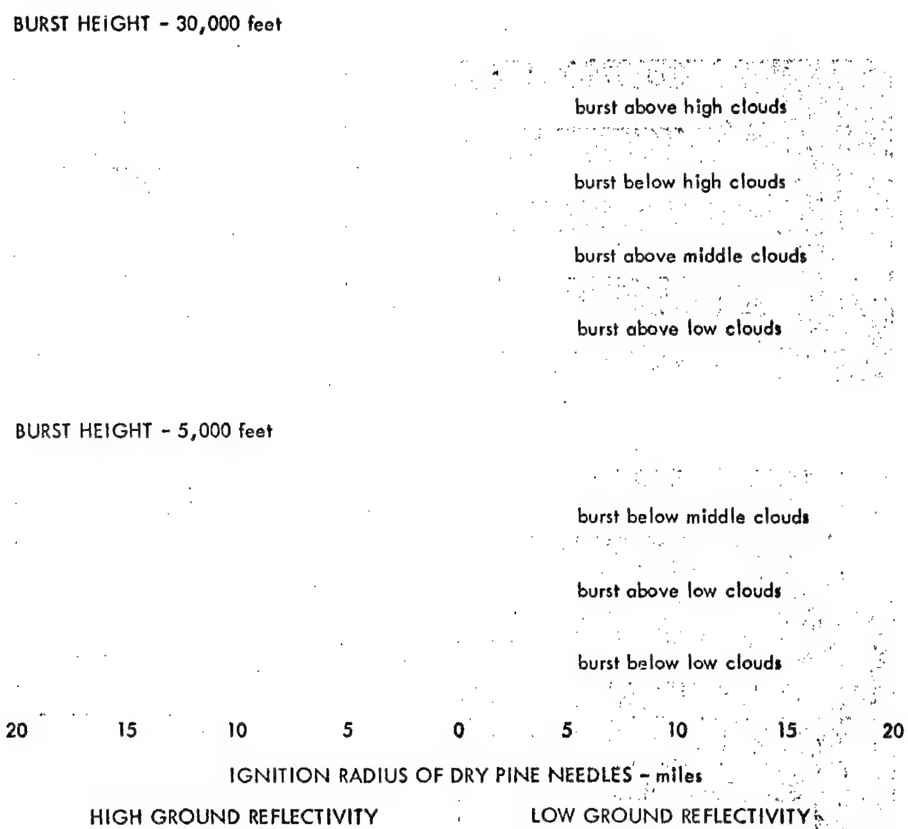


YIELD: 10 mt (using ignition requirements from Glasstone (1962) and Miller (1962)
35 mt (using ignition requirements from Martin (1959)

SOURCE: Cahill, et al (1962) and Stanford Research Institute

Figure 7

IGNITION RADIUS OF DRY PINE NEEDLES FOR OVERCAST DAY
(horizontal receiver, nonabsorbing and nonscattering atmosphere)



YIELD: 10 mt (using ignition requirements from Glasstone (1962) and Miller (1962)
35 mt (using ignition requirements from Martin (1959)

SOURCE: Schmall (1961), Haurwitz (1948), Neiburger (1949), and Stanford Research Institute

Using the methods developed in this present report, the results of the ignition of materials from low altitude air bursts may be applied to surface bursts and bursts above approximately 83-km (52 miles) altitude. For very high altitude atmospheric bursts (50 km to 83 km), the results can be related to the extremely short thermal pulse from a very low yield kiloton weapon at sea level. Unfortunately, since known studies on the ignition of materials do not apply for pulse lengths of less than about 0.1 second, the ignition capability of weapons detonated in this altitude range is unknown.* (See Rogers, 1963.)

Tests have been made on many materials other than kindling fuels, including plastics, metals, and heavy fuels. The results are recorded, in part, in Appendix B.

Modification of the Thermal Pulse by Materials

Some materials, such as heat-treated orlon, defy ignition by high intensity nuclear radiation. They may, however, transmit much of the energy and, therefore, are not good screening materials for use in clothing, curtains, and the like. The transmission characteristics of many screening materials have been tested both in the laboratory and in nuclear weapons tests. These materials include glass, window screening, plastics, and cloth of various kinds. The protection afforded by clothing, which is complicated by the air space between the clothing and the skin, has also been studied experimentally. The results of these tests are summarized in the Appendix B.

Interaction of the Thermal Pulse with Other Targets

Considerable research has been completed and is continuing on the effects on humans and laboratory animals of thermal radiation from nuclear weapons. These effects include flashburns of the skin, lesions on the retina, flash blindness, and keratitis (an inflammation of the cornea). A survey of studies on these effects is presented in Appendix B. Research has not been directed toward the effects of intense thermal radiation on farm animals and wildlife, which would be of interest in making national damage estimates.

Very little information is available on the effects of thermal radiation on living vegetation. A theoretical model for the killing effect of thermal radiation from low yield weapons is presented in one source (Fons, et al., 1950), but the theory was not tested. Somewhat more data are available on the screening of solar radiation by trees and

* Since the writing of this report, S. Martin of NRDL has undertaken additional work on the response of materials to very short thermal pulses.

forests, both in urban and rural areas, and these might be applied to the screening of thermal radiation from a nuclear fireball.

To relate the ignition of materials by nuclear thermal radiation to the threat of fires in cities, two surveys of the distribution of kindling fuels have been made. One was concerned with the density of exterior ignition points (Sauer, et al., 1953), and the other was concerned with the density of interior ignition points (Bruce and Downs, 1956). No studies attempt to relate these ignition point densities to the expected damage to cities although some crude estimates can be made from incendiary bomb damage reported in World War II.

The diffusion of thermal radiation within a city has not been studied. However, estimates might be developed similar to those made on the diffusion of solar radiation in forests of various densities of growth.

Interaction of Thermal Radiation with Blast and Radioactivity

Two classified paragraphs on thermal radiation have been deleted.

Fallout patterns from surface bursts may be grossly altered by mass fires. Laboratory experiments indicate that the pattern will broaden and shorten downwind if the fallout passes over convection currents from the fires (Broido and McMasters, 1959). Further work is required before definitive results can be stated.

Relationship of the Physical Environment to the Nuclear Fire Problem (Appendix C)

The physical environment as defined in this appendix includes the effects of weather and topography. In the preceding appendix interest was centered on the modification of only the direct thermal radiation by

the environment. In this appendix the importance of weather and weather statistics to the broader problems of ignition phenomena, fire development and spread, and ultimate damage estimates are considered.

Application of Weather and Climate Statistics to the Analysis of U.S Vulnerability to Nuclear Fires

Important sources of weather statistics are considered. As an example, these statistics are applied to the problem of predicting transmission of the atmosphere and area within which ignitions would occur from the direct thermal radiation of nuclear weapons. Such a treatment can be equally well applied to problems of fuel moisture content, fire spread, and other weather dependent variables. A discussion is included, concerning the implications of the capability of weather satellites to collect information on simultaneous cloud cover over the entire nation.

Effect of Weather on the Target System Vulnerability

The effect of weather in altering the vulnerability characteristics of a targeted area has been considered in Appendix C. The correlation of temperature and humidity with moisture content of fine (kindling) fuels, wood, and woodwork in structures has been studied extensively in the literature. The next step, viz., to estimate the variation of the vulnerability of fuels to ignition by intense thermal energy as a function of moisture content, has been satisfactorily completed (Martin, 1958). It has been found that once a fire is started, for kindling fuels the moisture content is not too important since the water evaporates quickly. When the moisture content of heavy wooden materials is greater than about 15 to 16 percent, these heavier members are difficult to ignite and incapable of propagating a vigorous fire. Below 12 percent moisture content, wood of any thickness is easily ignited, and propagation of fire is quite rapid. Extensive statistics have been collected on the moisture content in building materials as a function of time and geographic location. Such statistics may be useful in estimating fire vulnerability.

Studies on the effects of weather on fires and fire spread are manifold and detailed; many are discussed in the text. Because of the extensive experience of the Japanese with urban conflagrations, many of their studies appear to be of great value in understanding mass fire behavior even though the conditions of fuels, building densities, and other input parameters in Japan are somewhat different from those in the United States. Unfortunately, translations of the Japanese documents are not too accessible.

For forest fuels, an analytic model has been derived which successfully expresses the rate of movement of low intensity fires in a homogeneous fuel bed as a function of weather factors and fuel characteristics; see Fons (1946). Models which analytically describe the growth and movement of high intensity forest fires have also been devised, but these are not too reliable except in predicting very short-term fire behavior and are useful mainly to forest fire fighters. (Davis, 1959)

A better understanding of the influences of physical environmental factors, such as weather and topography, on the behavior of both urban and rural mass fires is expected as a result of current Office of Civil Defense sponsored research by the U.S. Forest Service and United Research Services.

Importance of Topography to Fire Vulnerability

Mention has already been made of the possibility of local topography shielding target areas from the direct thermal radiation of a nuclear detonation. Topography also influences the rate at which fires spread. The limited number of studies which treat this problem analytically are reviewed in Appendix C. Also, references are cited which describe the special effect of the fire whirlwind. This tornado-type wind activity is usually associated with ridge lines and is perhaps the most important direct cause of long-distance spotting and ember showers in forest fires.

Target Elements and Fire Processes (Appendix D)

When the direct thermal radiation from a nuclear weapon, modified by the environment, strikes susceptible targets on the ground, ignitions may occur over a large area. If these ignitions continue to burn until heavier fuels are ignited, the incipient fires may develop into full-fledged fires burning independently (group fires) or, in the most serious case, the convection currents from the individual fires may coalesce, creating a single mass fire. Appendix D reviews those studies which are pertinent to the understanding of these fire processes.

Materials and Fire Processes

A review is made of fire processes concerned with materials. These include (1) the ignition of materials, (2) flamespread, (3) potential heat in building materials, and (4) heat transfer through the ground and through underground shelter materials.

Materials may ignite because of exposure to heat of radiation, convection, or conduction. The actual processes of ignition and burning are extremely complex, and although attempts are being made to explain these phenomena, the results are far from complete. Radiation is the simplest heat transport phenomenon to analyze (see, for example, Appendix IV of A Study of Fire Problems, 1961). Unlike thermal radiation from nuclear weapons, the radiation of concern here is of relatively low intensity but may be sustained for comparatively long periods of time as in the radiation transmitted from a burning building to the facade of an adjacent building. It has been found that in the presence of a pilot flame, the intensity requirements for the ignition of materials are much less than if no flame is present. This fact has been used by some analysts (Salzberg, et al., 1961) to estimate the importance of firebrands in spreading fires between buildings. Downwind, firebrands provide pilot flames which lower the radiation requirement for ignition. Upwind, no such correction factor is applied. (Of course, firebrands will spread fires in other ways not considered in these analyses, for example, by falling in dry grass.)

Fire spread in forest fuels was considered in Appendix C where the effects of weather on fire behavior was discussed; in Appendix D, fire spread in building materials is considered. This subject is generally concerned with the rate at which flames spread along the surfaces of materials* and, in this respect, it is of particular interest in evaluating the effect of fire-retardant coatings. The National Bureau of Standards has an active program to analyze flamespread in various building materials, as well as a program to define and estimate the "potential heat" in building materials. The latter may be more important to the study of the combustion of structures than is the analysis of flamespread.

Estimates of heat transfer through the ground and through shelter building materials will be of interest to those persons concerned with the heat that might develop in underground fallout shelters during mass fires. Broido and McMasters (1960) computed the time for the temperature of the inside surface of a material to increase from 60°F to 90°F when the outside of the solid, originally at 60°F, was assumed to rapidly reach and be maintained at 2000°F. It was found that a slab of concrete or soil 1-foot thick would reach 90°F in about 3 hours. A 2-foot slab of concrete would take 10 to 23 hours, depending on its composition.

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* The rate at which fire moves in wood cribs, i.e., stacks of wood blocks, has also occupied the attention of several investigators; see, for example, Berl, 1961.

Other sources of information on heat transfer through the ground are studies made during forest fires. Some of these results, reported by Davis (1959), are presented in Tables D-III and D-IV.

Structures and Fire Processes

At least two methods have been used to categorize the combustibility of buildings. One method categorizes by the type of construction used and the other by the contents normally contained in the building. Statistics are available on the distribution of buildings according to fire resistance, both on a local and on a national scale. The literature on fire development within structures and fire spread between structures is extensive, and many attempts have been made to develop models describing the processes analytically. Standard methods that quantify the expected severity of building fires according to the fire resistance of the building walls have also been defined.

Structural Density and Its Importance to Fire Spread

A parameter that is often considered important to fire spread between buildings is the density of the buildings (i.e., ratio of roof area to total area). Wartime building densities of some Japanese and German cities are described in Appendix D. Data are presented giving (1) the minimum density required for firestorms or conflagrations (Civil Defense Urban Analysis, 1953) and (2) the percent of area which will be destroyed when exposed to mass fires, as a function of building density (Bond, 1949). However, since these data are based on wartime attacks on Germany and Japan, they will not necessarily apply to the cities of the United States. Furthermore, the reliability of the correlation of fire damage to building density is questionable, even for the wartime cases presented (see Fire Spread in Urban Areas, 1955).

Vulnerability of Humans in Mass Fires

A brief review of the effects of mass fires on humans is given in Appendix D. In addition to fatalities from burning, these effects may include casualties from oxygen depletion, carbon dioxide and monoxide poisoning, and excessive heat.

Vegetation and Fire Processes

In some cases, vegetation may shield structures and other vulnerable target elements. In others, it may enhance the destruction of nearby combustibles. A review is presented in Appendix D of the literature on these two aspects of the relation of vegetation to fire processes.

As a final topic in Appendix D, data are given for the fuel densities that were estimated in each of six mass forest (or brush) fires. These densities appear to be similar to those in some California cities although detailed surveys of the distribution of trees, shrubbery, and other vegetation in and around cities are apparently not available.

Countermeasures (Appendix E)

Many kinds of countermeasures have been proposed to limit the possible damage that might result directly or indirectly from thermal radiation in a nuclear attack. In Appendix E, a survey is made of the literature concerning many of these countermeasures. It is found that they fall into rather clearly defined groups as determined by the stage of development of the radiation and fire threat.

Countermeasures to Direct Thermal Radiation

There are at least eight kinds of countermeasures that would reduce the damage from the direct thermal radiation of a nuclear weapon. These are:

1. Artificial fog and smoke generation--pilot studies (Duckworth, et al., 1953) indicate that this may be an effective and feasible method for protecting a target area from thermal radiation.

2. Warning--it is estimated that 20 to 30 percent of the fatal casualties in Hiroshima and Nagasaki were caused by flash burns from direct thermal radiation (Glasstone, 1962). If sufficient warning is given and if individuals heed it, casualties from flash burns on the skin or on the retina of the eye should be practically nonexistent. Other countermeasures, such as the generation of smoke, would also be effective only if adequate warning is given.

3. Elimination of kindling fuels and general clean-up campaigns--such measures would reduce the number of points at which fires might start from thermal radiation.

4. Use of special fabrics--two types of special fabrics have been devised. One is resistant to ignition by high intensity thermal radiation and, hence, if used extensively in home furnishings and the like, it would reduce the number of possible ignition points. The other type of fabric is effective in shielding target elements from radiation. Such fabrics might be used, for example, as full window draperies to prevent ignition of the interior of buildings.

5. Eye protectors--developed mainly for use by the military, these include chemical devices and mechanical shutters. Their use is rather restricted because of their bulkiness or the restriction they impose on the field of view.

6. Skin creams--these have also been developed mainly by and for the military for use in tactical operations.

7. Special screens--window screens constructed of flat metal ribbons show promise of reducing the probability of ignition of the interior of structures. More work is required, however, to estimate their effectiveness in countering thermal radiation from megaton yield weapons.

8. Special paints--smoke producing and foam producing paints have been considered, and some of the literature pertaining to them is described in Appendix E.

Countermeasures to Incipient Fires

Discussed under this heading are a few of the many reports concerned with (1) fire resistant and fire retardant materials and paints, (2) confinement of fires, (3) chemical extinguishers and fire inhibiting chemicals, and (4) specially designed sprinkler systems.

Countermeasures to Group Fires

Although professional fire fighters would be invaluable at any and all stages of an attack, they would probably be most effective at that stage where individual structures are afire but the flames have not yet coalesced into mass fires. Stricter building and fire codes might aid in preventing group fires from developing into mass fires. Elimination of surrounding dry vegetation, such as exists in many California communities, and the use of fire retardant paints would help prevent the spread

of fire between buildings. (Brown, 1962, has estimated that it would require a 7 to 20 times greater heat intensity for fire to jump a firebreak if opposing buildings were painted with fire retardant paint rather than ordinary paint.) Recently developed chemical fertilizers, which make vegetation fire retardant, appear to offer promise of reducing the fire hazard of trees and shrubbery. Since these fertilizers are nontoxic to animals, they should also prove useful in alleviating the fire hazard of grazing and crop lands.

Countermeasures to Mass Fires

Measures to resist or control damage from conflagrations or firestorms include active firefighting, development of cities with open spaces and canals to act as firebreaks, construction of airtight underground shelters for the population, and planning for mass evacuation from fire and blast areas. All of these countermeasures were found to be effective in Germany and Japan during World War II in reducing casualties and structural damage.

Some studies have been made on the costs involved for specific countermeasures. The economics of fire fighting have been studied by forest and urban fire fighters for many years, but only recently have the costs of fighting mass forest fires been subjected to the methods of operations analysis; see Shephard and Jewell (1961) and A Study of Fire Problems (1961). At the present time, however, there is no general analytic method to demonstrate the cost-effectiveness of countermeasures to a nuclear threat.

III CONCLUSIONS AND RECOMMENDATIONS

Before identifying areas where additional research is required, it is important to indicate that there is a distinction between fire research for Civil Defense and fire research for other purposes. Consider, for example, the problems of the Forest Service. The Forest Service is especially concerned with seasons of high fire susceptibility which occur at widely varying times in different sections of the United States. In contrast, the evaluation of the threat of fires from a nuclear attack should consider the threat of fires to the entire nation simultaneously. As another example, with the exception of the Rocky Mountain area, the majority of forest fires are caused by people rather than by lightning; see Folweiler and Brown (1946). Hence, most peacetime forest fires begin at ground level from burning debris, cigarettes, campfires, and the like. In a nuclear attack, however, the thermal flash striking the tops of evergreens might be adequately attenuated before reaching the decayed kindling fuels on the forest floor. On the other hand, dead foliage in the tree tops of deciduous woods during certain seasons of the year might cause crown fires, which are the most rapidly moving and dangerous of all forest fires. These are only a few of the differences between the fire problems of the Office of Civil Defense and those of other fire-oriented groups.

As indicated by the above examples, the Office of Civil Defense should recognize that the protection of people and property from fires caused by a nuclear attack presents unique problems. They are not necessarily identical with those of the Forest Service, urban fire departments, fire underwriters, the basic researcher, or even the planner of military offense strategies. Although the Office of Civil Defense must use the wealth of experience and the research capabilities of these groups wherever applicable, it should develop in detail its own fire research program based upon goals which will lead to a feasible accomplishment of the civil defense missions.

The appendixes contain detailed descriptions of the fire research accomplished to date, indicate the important problems remaining, and suggest approaches to the solutions of these problems. Broad conclusions and recommendations derived from the appendixes are outlined below.

Formulation of Quantitative Goals--As a prime prerequisite to all fire research sponsored by the Office of Civil Defense, an analysis should be made outlining specific quantitative goals which, if achieved, would materially assist in the conduct of the civil defense mission. As a simple

example, a goal of civil defense might be to estimate the earliest possible time that shelter occupants could be safely removed from shelters within fire damaged areas. Starting from this goal, important parameters could be identified, giving specific direction to the research. Such parameters, for this case might be the temperature history of the fire, the radioactivity of the area (if any), the amount of rubble in the streets, and the like. Although research effort should be expended on detailed studies of these unknowns, it is not expected that they will be well understood for some time. Parametric studies might establish bounds which would give initial results, pending more scientifically precise investigations.

Strategy and Tactics--In the past, little effort has been applied to the importance of the strategy and tactics of a possible attack from the standpoint of fire damage. A recognition of these inputs is necessary for understanding the fire threat posed by nuclear weapons. In particular, research activities should be undertaken which would include, but not be limited to, the following: a description of the thermal effects of multiple weapons on a target area; a study of the importance of timing of an attack on the parameters affecting the vulnerability of the entire United States simultaneously; an investigation of the importance of warning to civilians and professional fire fighters; additional research on the effect of altitude on the thermal partitioning of energy and the pulse shapes of weapons, particularly for the intermediate altitudes (10 km to 80 km--6 to 50 miles).

Weapon Phenomena--Analysis of the effects of nuclear weapons will be incomplete unless further research effort is expended on certain weapon phenomena. Strong convection currents from mass fires may seriously alter the results predicted from detailed fallout models. There are also indications that with large weapons, the resulting fires may be extinguished by the follow-on blast wave. Furthermore, the direct effects of atomic bursts on clouds and fog is practically unknown.

Response of Materials--The effects of actual and simulated weapon pulses on materials is perhaps the most thoroughly understood phenomenon in the entire fire research area. Even here, however, work remains to be done. In particular, investigation is required on the effects of extremely short, high intensity pulses such as would be experienced from a high altitude burst.* Also, study is needed on the effects on materials of overlapping thermal pulses from more than one weapon.

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* See footnote on page 17.

Urban/Rural Interactions--Almost invariably, the study of the fire potential of weapons has been restricted either to forested areas or to urban areas. A unified study is required which will consider the effects radii of weapons, the size of cities, and the interface between the cities and forested areas to give an indication of the interaction between urban and rural fire susceptibility, fire behavior, and fire defense.

Ignition Points--More precise definitions of the important ideas of ignition points and ignition densities should be made, and parametric studies should be conducted on their variation with attack parameters. A study should be undertaken to develop these quantities into factors which will apply to the ultimate aims of civil defense.

Japanese Data--A systematic effort should be made to interpret (both linguistically and mathematically) the wealth of Japanese experience with conflagrations and to apply the results to the study of mass fires in the United States.

Coalescence--Before firestorms and other fire processes can be fully understood, much more information is required on the problem of the coalescence of fires, both within the area of effects of a single nuclear weapon and between such areas in the case of attacks with more than one weapon on a target.

Countermeasures--Although it is evident that effort should be continued on the development of passive countermeasures for the entire spectrum of potential fires, an equally important effort should be directed toward methods for getting promising countermeasures widely accepted by the public. Most countermeasures would not be effective unless incorporated on a large scale. Since past experience has shown that the usual public reaction is one of apathy, legal steps may be required to accomplish vigorous public participation. This may necessitate more stringent legal restrictions on building densities and other construction codes, as well as laws to allow fire fighters legal protection when choosing the most effective method of attacking a fire.

Functional Systems--Studies should be made of the fire vulnerability of functional systems, such as the power industry, agriculture, and transportation and communication systems. In particular, the susceptibility of the petroleum industry to nuclear thermal radiation, fire, and fire spread should be considered. With the exception of studies on the vulnerability of military installations, no studies apparently have considered the vulnerability of a functional system to the particular threat of nuclear fires.

Appendix A

SUMMARY OF DATA EMANATING FROM OUTSIDE THE TARGET SYSTEM

Probably one of the least acknowledged influences on the fire potential of nuclear weapons is the importance of input data emanating from outside the target system. In particular, attack strategies and tactics and the possibility of strategic warning greatly influence the depth and breadth of the research required to understand and counter the threat of fires from nuclear attacks. Virtually no work has been done relating these topics to the threat of nuclear fires.

There are perhaps good reasons for this weakness. For one thing, many investigators are specialists in fire processes, material ignition, and the like and have only peripheral interest and experience in strategy and tactics. Second, it is undoubtedly true that not too much reliable information can be gleaned at this time since so little is known about the basic processes of fire and fire spread.

Even a somewhat hasty reflection on the input data, however, adds perspective to the fire research, presents new challenges, and, in some cases, restricts the otherwise unlimited range of the variables. A brief survey of some of the important input data and their influence on fire research programs follows.

General Characteristics of an Attack

A nuclear attack on the United States could occur under any number of different circumstances. One can identify some of the more likely types of attack and their effects on the parameters of any fire study. Table A-I lists five possible attack types and their probable effects on timing, targeting, and warning.

For the case of a deliberate optimum attack by the Soviet Union, optimum timing is that timing which would create the maximum damage from all weapon effects.

Table A-I

EFFECT OF ATTACK TYPE ON DAMAGE ASSESSMENT PARAMETERS

Attack Type	Probable Effect		
	Timing	Targeting	Warning
First strike: deliberate	Optimum	Counterforce or mixed	None-some
Second strike: retaliatory	Time shift from optimum in attacker's country	Population	Some-maximum
Pre-emptive: strike from fear	Random	Counterforce or mixed	Some
Accidental	Random	Single target to all-out pre-emptive	None
N-th Country	Optimum	Population-few targets	None

Source: Stanford Research Institute.

The timing, however, would be particularly important in evaluating fire damage. As will be seen later, the cloud cover, the moisture content of materials, the seasonal winds, and many other critical fire parameters are indirectly affected by the timing. Furthermore, an unhurried attack is likely to produce the most reliable results.

Although a second strike by the enemy seems highly unlikely at first glance, the first strike could have been made by a country other than the United States. Hence, it is of more than academic interest to include the retaliatory strike as a possibility, at least in planning for future eventualities. If an attack were timed by an aggressor to create maximum damage effects on the Soviet Union, the retaliatory attack on the United States might create less than maximum possible damage because fire susceptibility varies greatly with geographical regions. In

studying the retaliatory attack, one could probably choose the timing to be on the order of a few hours or a day later than an optimum attack on Russia.

An accidental attack could occur under many different circumstances. It might be caused by a single missile being launched by error, a communication error at a particular weapon missile site, a breakdown in a warning system (such as has been caused by meteoric showers in the past), or other unusual circumstances. Hence, the accidental attack could involve a single target, or it could involve the entire country.

In an N-th country attack, it is likely that any country intelligent enough to develop or control a nuclear device and sinister enough to employ this strategy would plan to create maximum damage on a very few population targets. This would create the shock necessary to involve the major world powers in a nuclear exchange and would require a minimum of cost and complexity to the instigator.

In summary, Table A-I presents some logic for choosing certain combinations of parameters in assessing possible fire damage from nuclear attacks. The parameters which lead to optimum damage are likely to involve little or no warning for the United States, and the targeting may be either counterforce, population (on an individual target basis), or mixed. A retaliatory attack would probably involve only population targets with either some or a great deal of warning. The effects of timing should be bracketed or treated in a random variable fashion for the case of counterforce or mixed counterforce-population attacks with some warning. The accidental attack is the most difficult to evaluate since there would be no warning, and the targeting, as well as the timing, would be essentially of a random nature.

Attack Input Parameters

Targeting

The choice of targets is an input parameter which is at the discretion of the attacker. Although the United States would not know this choice prior to an actual attack, there may be reasons to believe a counterforce, a population attack, or a mixed attack might be favored. The effect of the choice of targets on the threat from fires cannot be ascertained with any reliability at this time since the physical principles of ignition and fire spreadby nuclear weapons are not fully understood. Jewell and Willoughby (1960) have taken the approach of estimating the burnout area for various cities and military targets if

each were attacked by a single weapon. However, there is no discussion of the total damage which would be created under various assumed targeting doctrines.

Another approach which obviates a detailed study of fire effects and yet gives some insight into the dependence of the fire threat on the choice of targeting will now be discussed.

Consider first a counterforce attack. A target list has been chosen which contains ICBM forces, SAC bases, naval operating bases, and other military targets. The locations of these targets have been estimated; for each United States city with a population greater than 100,000,* the military targets within 200 km have been listed, together with the range to each of the cities. The radius within which 95 percent of the population of each city resides has also been determined, using the analysis of Weiss (1961); this radius has been subtracted from the range to the pertinent counterforce targets; see Figure A-1. If one assumes that military targets are attacked, the calculation represents the range to which weapon effects must extend to damage the city or threaten the population. These data have been accumulated in Figures A-2 and A-3 to show the number of cities threatened as a function of the radius of weapons effects. Figure A-2 includes predominantly ICBM target complexes, while Figure A-3 includes <u>all</u> counterforce targets in the United States. Also included is the total population threatened and, in Figure A-2, the areas of the threatened cities have been accumulated as well.

Since some of the targets have been hardened and would require ground bursts for destruction, more energy would go into shock and less into thermal radiation. Hence, the area of initial ignitions would be reduced. The broken lines in Figure A-3 show an adjustment for this effect, assuming a decrease in range of thermal ignitions for hard targets. From these results, it is seen that considerations of ground bursts against hardened military targets do not significantly alter the threat to the populations of nearby cities as compared to that posed by an all air-burst attack.

It has sometimes been argued that the analysis of fire spread in cities has become an academic undertaking in these days when the area of destruction of a single weapon is larger than the city itself. Figures A-2 and A-3, however, show that many cities are considerable

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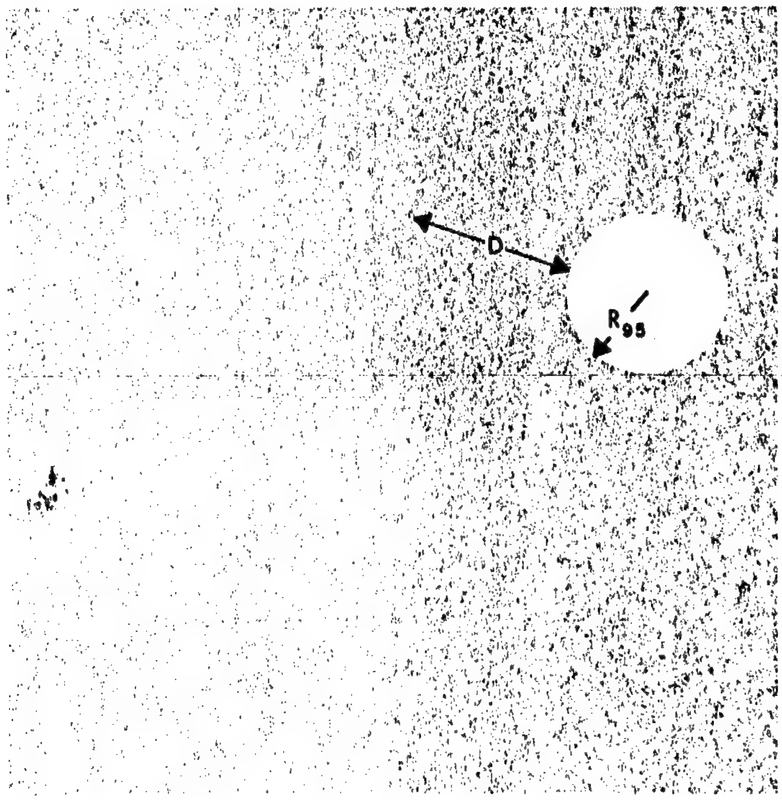
* According to the 1960 census, 128 cities in the United States have populations greater than 100,000.

Figure A-1

SCHEMATIC FOR COUNTERFORCE ATTACK



X = MILITARY TARGETS
R_{95} = RADIUS WITHIN WHICH 95% OF THE POPULATION RESIDES
D = DISTANCE AT WHICH WEAPON EFFECTS HARM OR THREATEN THE POPULATION

SOURCE: Stanford Research Institute

Classified Figure A-2 on cities located near military targets has been deleted.

Classified Figure A-3 on cities
located near counterforce targets
has been deleted.

distances from military targets. Consequently, in a counterforce attack the vulnerability of cities to thermal ignition and fire spread is most important.

A similar sort of approach may be used in considering population attacks. In this example, use was made of actual 1960 population data to determine number of people in every 5-km square. Assuming attacks on the 30 largest cities, Figure A-4 shows the accumulation of population as a function of range from these cities. Individuals in overlapping regions are counted only once. Data are also presented for the case of the 50 largest cities being targeted. From consideration of these examples of counterforce attacks and population attacks can be derived some insight of the importance of the range of effects of weapons, whether fire, blast, or radiological.

Delivery Vehicle

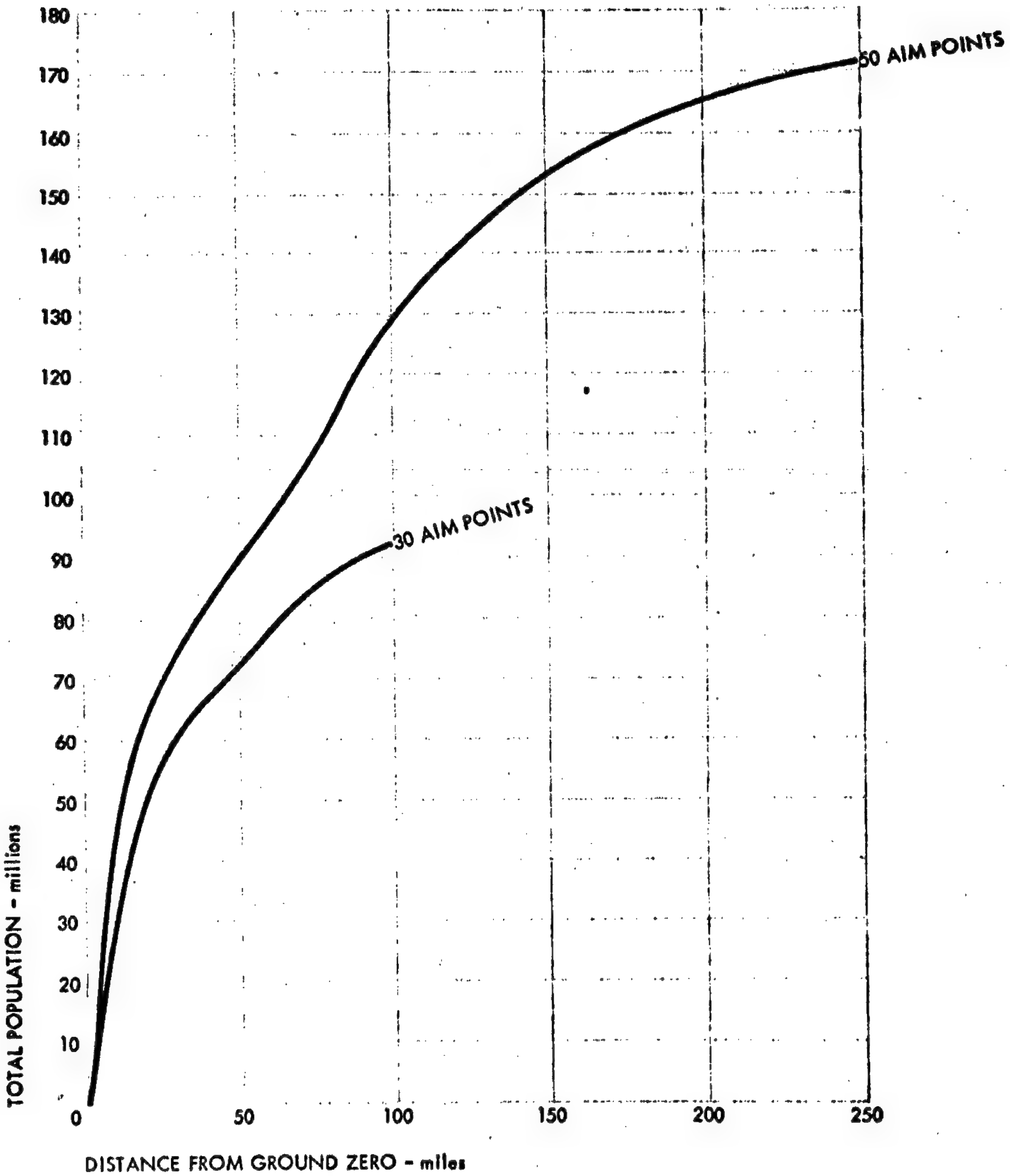
The types and numbers of missiles and bombers in the Soviet stockpile, as well as their ranges, vulnerability, and reliability, are all important to the assessment of the threat they pose to the United States. A few special remarks about delivery vehicles can be made, however, which are of particular concern in the study of fires.

Payload Requirements and Soviet Capabilities

Claims have been made by Brown and Real (1960) and Piel (1962) that it will soon be feasible for the Soviet Union to detonate a gigaton (1,000 mt) weapon at satellite altitude over the United States and, further, that a single such weapon "could sear six western states." One question to be answered in analyzing the credibility of this statement is whether the thrust of the Soviet missiles is sufficient either to launch such a device into a controlled orbit or to deliver it by ballistic trajectory over the United States. A second question is, of course, whether large yield weapons burst at very high altitudes would actually create the widespread damage claimed. This latter problem and associated phenomena are considered by Smith and Stapleton (1959), Stuart (1961), Hoerlin (1962), Biggs (1963), and Latter, et al. (1961); an unclassified discussion was developed by Passell (1963) and Miller and Passell (1963).

Figure A-4

TOTAL POPULATION VS DISTANCE FROM GROUND ZERO



SOURCE: Stanford Research Institute

Classified paragraph concerning Soviet capabilities has been deleted.

Accuracy Requirements

Because of the spreading of fires and the large ignition areas, the accuracy of the weapons is not a critical factor in the weapons effectiveness in igniting fires.

Salvo Attacks

Classified paragraph on salvo attacks has been deleted.

A salvo attack is a particular threat for at least three reasons:

1. Since the thermal energy pulse from more than one warhead would be the sum of the energies from the individual pulses, the nearly simultaneous detonation of a salvo of missiles would be most effective in producing ignitions. No studies have been made on the effect of overlapping thermal pulses on materials.

2. Unlike blast, fires may spread from the areas ignited by the individual missiles and may coalesce into a single firestorm or conflagration. Only limited experiments have been made on the coalescence of fires and flames in laboratories and field tests. These will be discussed in more detail in the paragraphs concerned with fire spread and

Classified Figure A-5 pertaining to Soviet payload capabilities has been deleted.

Classified Figure A-6 on Soviet capabilities has been deleted.

Classified Figure A-7 on yield delivery capability has been deleted.

fire development. In general, the laboratory studies, such as Putnam and Speich (1961), are difficult to scale to the mass fires of concern in this paper. Furthermore, they are artificial in the sense that fuel is supplied at a constant rate from gas jets, with no natural spread at the base of the flame. In the Camp Parks burn field test, Broido and McMasters (1960), it was hoped that the fires from simultaneously ignited piles of wood (measuring 20 × 15 feet, 7 feet high, and spaced 12 feet apart) would coalesce into one mass fire. This occurred to some extent, but 10 minutes after ignition the merging flames had separated into a group of individually burning fires. Within another 10 minutes some of the piles had stopped flaming. From these and other limited studies, there is still very little known about the coalescence of fires into mass fires.

Classified paragraph on salvo attacks has been deleted.

<u>Warhead</u>

Five classified paragraphs concerning multiple warheads have been deleted.

Classified Figure A-8 pertaining
to re-entry weight has been deleted.

Classified Figure A-9 on yields
has been deleted.

Special Warheads

There is a possibility that special warheads could be developed to enhance the fire effects. For the case of extremely high altitude shots, the ground thermal effects would be caused by the reradiation of energy from a pancake-shaped layer at about 83 km (52 miles) altitude. A more efficient method for creating fires would be to generate the heat at the point of detonation. This probably would require considerable mass in the bomb case and for this reason might not be practical. No research has been applied to this problem.

In detonations at extremely high altitude, at least half of the energy is radiated directly to outer space. In atmospheric shots, the loss is not so great because of scattering. It might be possible to reduce the loss to outer space by first creating a reflecting layer of particles above the altitude of detonation. Some vaporization might occur prior to reflection. The possibility of such a tactic has not been considered in any detail.

A third possibility for increasing the fire effectiveness of a warhead would be to increase its initial black-body temperature. It appears from very brief considerations that this would be very difficult.

Classified Figure A-10 on ignition area has been deleted.

Yield

The area within which fires would be ignited by a nuclear detonation is, of course, critically dependent upon the yield of the weapon. This relationship is not at all simple. Many complex intermediate variables are involved and only with the most severe assumptions has the ignition radius been explicitly expressed as a function of the yield.

The variable most directly affected by the yield is the thermal pulse shape. The shape of the pulse determines the response of ignitable materials--not the total energy falling on them. For example, on a hot day, the earth receives a thermal pulse from the sun with a total energy on the order of 700 calories/cm^2; yet as little as two calories/cm^2 from a nuclear detonation will ignite some materials.

Considerable work has been done on the effects on materials of thermal pulses from sea-level nuclear detonations. No work has been done, however, on ground bursts or bursts at higher altitudes. In this paper, the thermal pulse at high altitudes has been related to one of different yield at sea level in order to make the extensive tests on ignition of materials applicable to the other altitudes. This is one of the important reasons for considering the thermal pulse shape and its variation with yield.

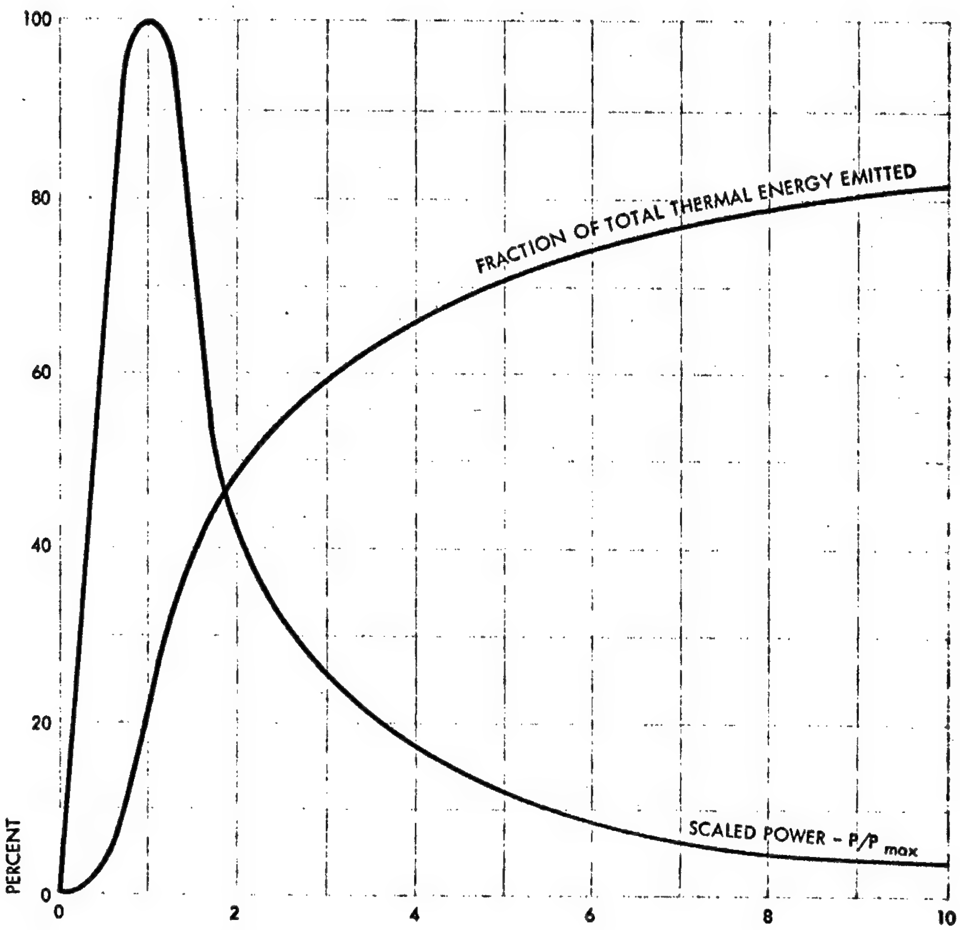
By definition, the thermal pulse is the curve representing the power emitted as a function of time after detonation. Since power is energy per unit time, the thermal pulse is expressed in terms of calories (or kilotons or megatons) per second. The integral of the thermal pulse from time of detonation to infinity gives the total amount of thermal energy emitted by the weapon. This will be some fraction of the total yield of the weapon, and this fraction represents the thermal partitioning of the yield.

Extensive weapon experimentation has shown that the thermal pulses from all weapons burst at low altitudes are of identical shape when plotted on logarithmic graph paper. By a shifting of the axes, the curves can all be superimposed on a normalized thermal pulse which has a maximum power of one unit at a time of one unit. On arithmetic paper, this means that all thermal pulse curves may be superimposed on the normalized pulse by a suitable multiplicative scaling of the axes.

The generally accepted unclassified version of the thermal power pulse is shown in Figure A-11. Included on the same graph is the percent of the total thermal energy emitted as a function of time. The scaling of the thermal pulse is as follows:

Figure A-11

SCALED FIREBALL POWER AND PERCENT OF THERMAL ENERGY VS SCALED TIME IN SECOND THERMAL PULSE OF A SEA-LEVEL AIR BURST



SCALED TIME - t/t_{max}

$P_{max} \approx 4W^{\frac{2}{3}}$ kt/sec

$t_{max} \approx 0.032W^{\frac{1}{2}}$ sec

$E_{TOT} \approx \frac{1}{3}$ W kt

SOURCE: Glasstone (1962)

$$t_{max} = 0.032\ W^{1/2} \text{ seconds} \quad (1)$$

$$P_{max} = 4\ W^{1/2} \text{ kilotons per second} \quad (2)$$

To find the total energy emitted, E, one integrates the power, P, from t = 0 to t = infinity:

$$E = \int_o^\infty P\,dt = P_{max}\,t_{max} \int_o^\infty (P/P_{max})\,d(t/t_{max})$$

$$= 0.128\ W \int_o^\infty (P/P_{max})\,d(t/t_{max})$$

Numerical integration shows that the integral of the scaled curve is about 2.6 and hence total energy is approximated by:

$$E = 1/3\ W \quad (3)$$

The classified version of the thermal pulse has been deleted.

The square root scaling given in the Effects of Nuclear Weapons predicts times about 30 percent too short at 1 kt and about 30 percent too long at 3.8 mt. At higher yields, the error would be even more significant. The importance of these differences in predicting areas in which ignitions would occur has not been ascertained. For further details on the thermal pulse, see Appendix F.

Effect of Range

The thermal power and total thermal energy as given by equations (2) and (3) or (2") and (3"), respectively, represent the thermal radiation at the surface of the fireball. To calculate the amount of energy per unit area falling on a surface at greater distance R, the total thermal energy emitted by a nuclear detonation is assumed to be distributed evenly over a spherical surface of radius R. Then the energy on each square centimeter of this surface is given by:

$$Q = \frac{E}{4\pi R^2} \qquad (4)$$

Classified Figure A-12 comparing classified and unclassified versions of thermal pulse shape has been deleted.

where E is in calories and R is in centimeters if Q is in cal/cm^2. It is often assumed that the modification of Q by the atmosphere and the earth's surface can be taken into account by multiplying the value for Q in the above equation by T, the transmission factor. This factor is defined as the ratio of incident radiation in the presence of the atmosphere and the earth's surface to the energy received in the absence of such environment. Thus,

$$Q = \frac{TE}{4\pi R^2} \tag{5}$$

The value of T is very difficult to ascertain as a function of atmospheric parameters and range. It may even be larger than unity in the case of reflections. An expression commonly used to approximate atmospheric attenuation due to both absorption and scatter for all wave lengths is given in terms of a mean exponential attenuation factor

$$T = e^{-3.912R/V}$$

where V, the visibility, is loosely defined as the distance at which it is just possible to distinguish a large dark object against the horizon; see Broido and Trilling (1955). A more exact definition for visibility, although not acceptable to all physicists, is that visibility is that distance through an atmosphere at which the direct visible radiation from a black body is attenuated down to 2 percent of its original value. Other empirical expressions for T are presented in Jewell and Willoughby (1960). Of course, these approximations do not consider reflections, cloud layers, and the like. For a detailed account of the problems of computing the transmittance, see page B-16 and Passell (1963).

If the values given in equation (3) are used for the thermal energy partition, viz., E = 1/3 W, and adjusted for units:

$$Q = \frac{1.04\ WT}{R^2}\ \text{cal/cm}^2 \tag{6}$$

where W is in kilotons, R is in miles, and T is a dimensionless fraction (dependent on R and atmospheric conditions).

Altitude

The altitude of detonation significantly affects the pulse shape and hence, the ultimate thermal damage created by a nuclear explosion. The description of the pulse for ground bursts is quite well understood. As the altitude increases, the pulse shape, as evidenced by a limited number of weapon tests, can be explained by empirical laws. The interaction of the blast and electrodynamic phenomena is so complex, however, that there is no accepted explanation for complicated wave forms that have been observed in the higher altitude bursts ($>$ 50 km--31 miles).[1] Hence, the empirical scaling laws are not too reliable. For the case of shots in outer space, recent test data are of little value in the study of thermal radiation. These tests were made for the purpose of observing the effects of high altitude explosions on communication and were of such low yield that the earth's atmosphere phosphoresced but did not heat to incandescence. Hence, the thermal flux information was of little importance.

To understand the phenomena of very high yield weapons burst at very high altitudes or in outer space, a theoretical study was undertaken at SRI in conjunction with this contract, Miller and Passell (1963). The reason thermal phenomena at these altitudes could be investigated is that the hydrodynamic shock wave has little effect on the thermal pulse, and hence the complicated interaction of the hydrodynamic and electromagnetic forces may be neglected. These theoretical calculations agree fairly well with the limited experimental data available.

In summary, it is felt that the thermal effects of ground and low altitude bursts are well understood by virtue of the weapons test; the thermal effects for extremely high altitude ($>$ 50 km, 31 miles) and outer space shots are presumably known by virtue of theory; but the intermediate altitudes are difficult to explain and the empirically derived scaling laws are not too reliable. A summary of the influence of altitude on the weapon pulse follows. For greater detail, see Appendix B.

Surface Bursts

A surface burst is, of course, one in which the fireball touches the ground. The Effects of Nuclear Weapons states that between 1/4 and

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1. See Nuclear Weapons Blast Phenomena, 1960, and Hillendahl, Vol. III, 1959.

1/7 of the total energy of a surface burst becomes thermal energy and that this can be introduced into equation (5), giving:

$$Q = 0.8 \text{ to } 0.5 \frac{WT}{R^2} \text{ cal/cm}^2 \qquad (7)$$

which represents the energy/cm^2 striking a surface facing the detonation and at a distance R from ground zero. Another unclassified source, Kester (1961), explores the geometric effects to a greater extent than does The Effects of Nuclear Weapons (1962), in considering energy flux from air bursts, ground bursts, and intermediate bursts. It considers not only targets on the ground but also targets in the air. For the special case of ground targets, the calculations give an energy flux identical with the air burst equation (5), the reason being that although the energy is concentrated over half a sphere, thereby doubling the flux, the target sees only one side, i.e., half of the fireball.

Classified paragraph on surface bursts has been deleted.

Very High Altitude Bursts (50-83 km, 31-52 miles)

For very high altitude bursts the pulse duration is practically independent of the yield and the power is directly proportional to it; see Appendix F and Miller and Passell (1963). Although the pulse shapes are somewhat different from those of low altitude air bursts, it is probable that their effects on materials can be approximated by the low altitude air burst scaled as follows:

$$P_{max} = 14.5\ W\ (10\text{-}0.036h) \times 10^{3}\ \text{kt/sec} \qquad (11H)$$

$$t_{max} = 2.5 \times 10^{-7}\ (10^{0.054h})\ \text{sec}\ , \qquad (12H)$$

where W is in kilotons and h is in kilometers. Numerical integration gives:

$$E = 5 \times 10^{-3}\ W\ (10^{0.018h})\ \text{kt}\ . \qquad (13H)$$

As an example, at H = 80 km, these values become:

$$P_{max} = 19\ W\ \text{kt/sec}$$

$$t_{max} = 5 \times 10^{-3}\ \text{secs}$$

$$E = 0.2\ W\ \text{kt}\ .$$

There is no way to say whether these values are correct, since the pulse shapes differ from the low altitude air bursts. However, over the critical portion of the thermal curve, i.e., the portion where most of the energy is released, the curves enclose about the same area and have approximately the same shape as do the curves from the Teak tests.

Classified information on very high altitude bursts consisting of four paragraphs has been deleted.

Classified Figure A-13 on yield for
thermal pulse shape has been deleted.

Outer Space Detonations (> 83 km, 52 miles) (Miller and Passell, 1963)

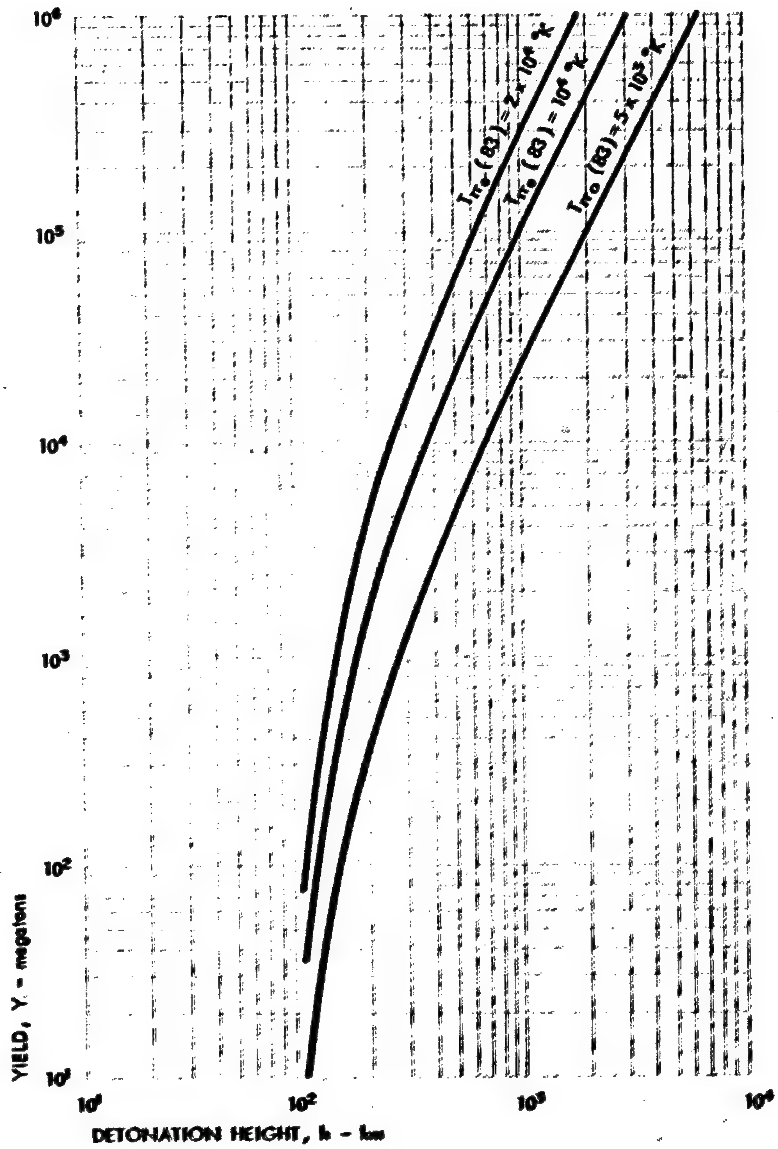
In outer space detonations a large yield weapon will heat a pancake-shaped area at about 83 km altitude. The radius of this fireball will be approximated by h - 83 km, where h is again the altitude of burst in kilometers. The temperature to which the layer will be heated is a function of yield and altitude of detonation, as shown in Figure A-14. The thermal pulse will be derived from the reradiation of this layer and will continue over a considerable length of time.

A function proportional to the thermal pulse of the reradiating layer for three different initial temperatures is plotted in Figure A-15. These curves represent the efficiency of the reradiation caused by the atmospheric passband. Two other power degradations must be taken into account. Only about 4/5 of the energy of the device is in the X-rays which heat the layer, and about 1/4 of that is absorbed in the reradiating layers. Hence, multiplying the values in Figure A-15 by $(1/4 \times 4/5)W = 0.2\ W$ gives the actual power pulse. Bracketing curves on the scaled power pulses are shown in Figure A-16 and an approximation by a low altitude air burst is superimposed.

Classified paragraph pertaining to pulse shapes has been deleted.

Figure A-14

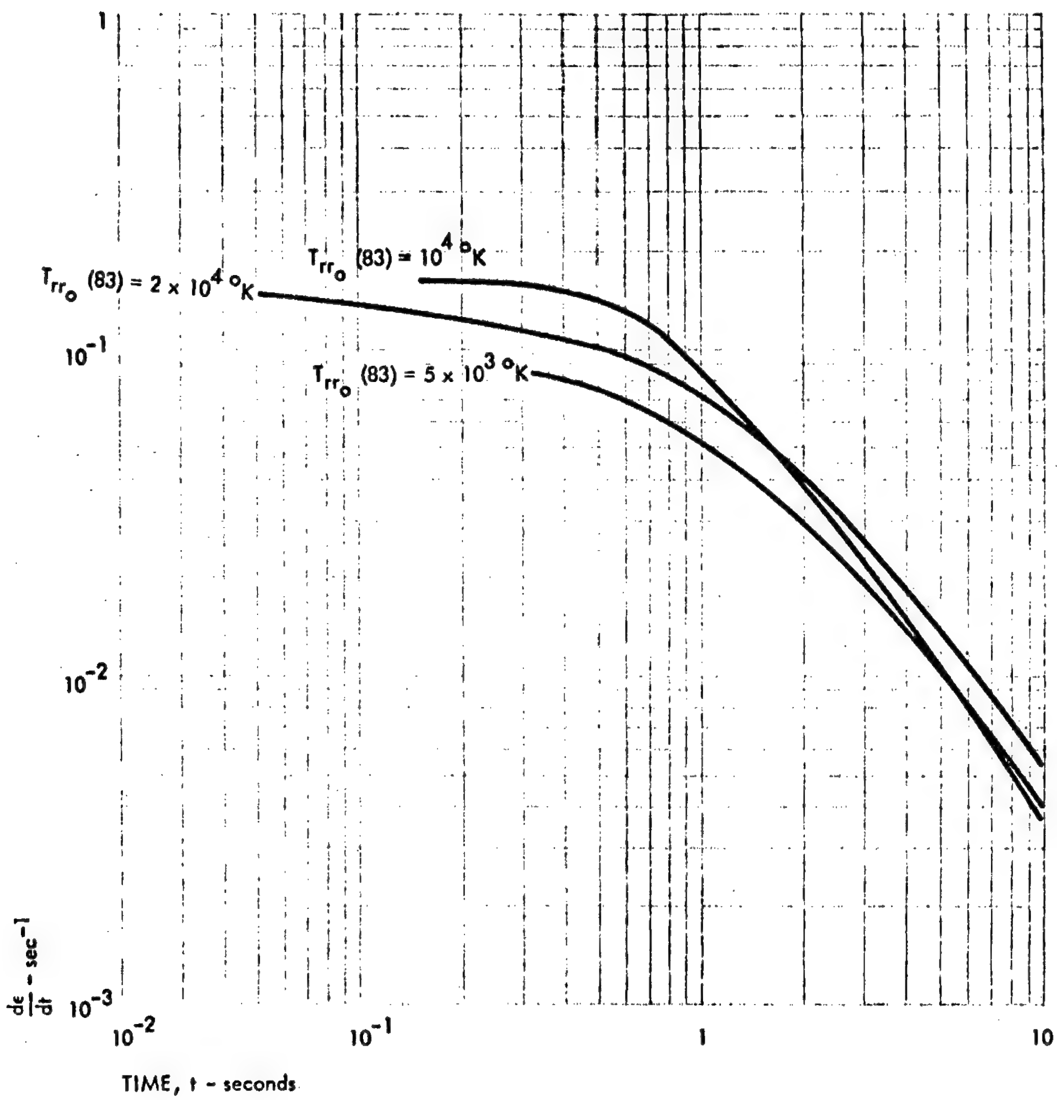
TEMPERATURE OF RADIATING LAYER
(outer space detonation)



SOURCE: Miller and Passell (1963)

Figure A-15

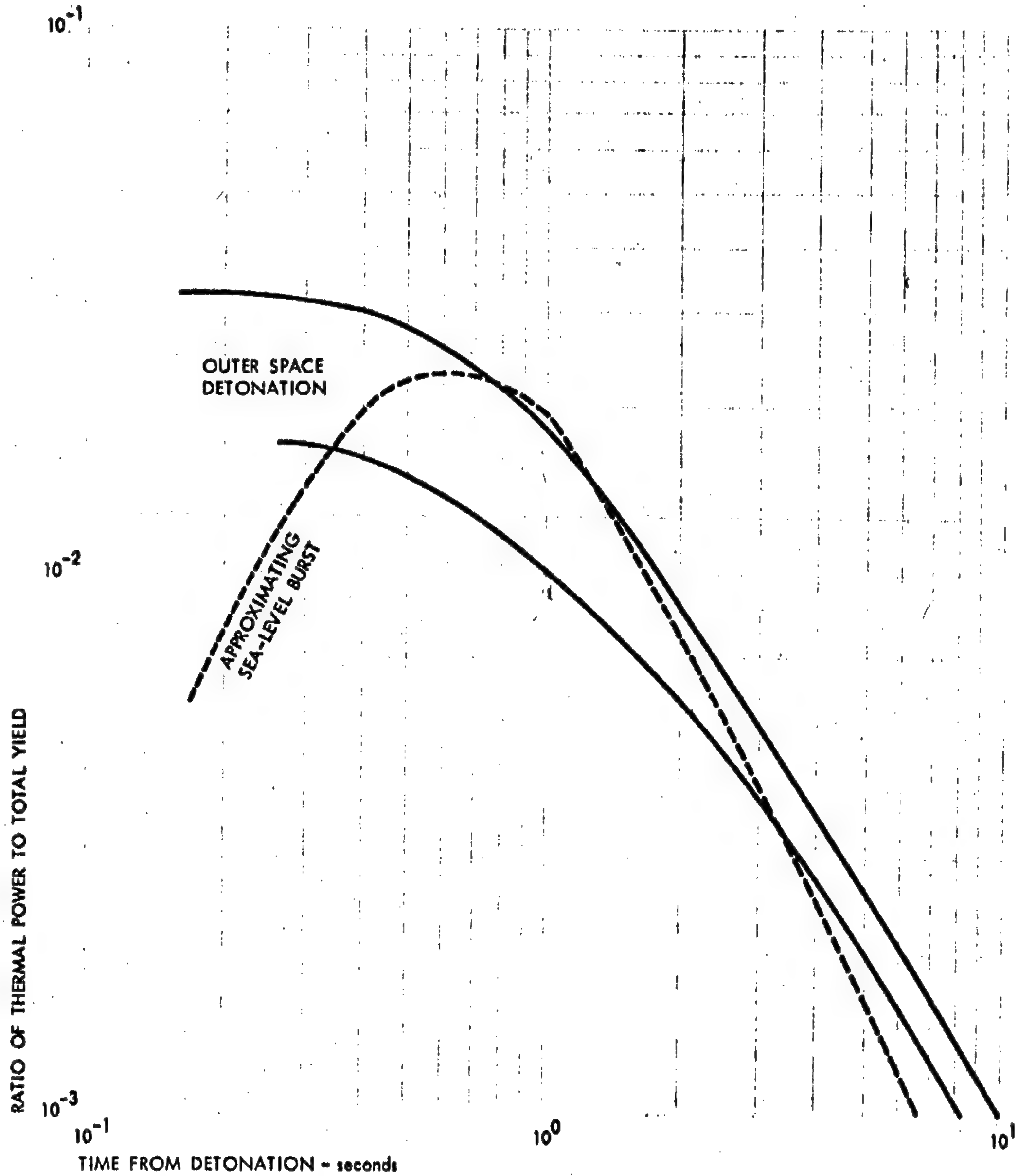
QUANTITY PROPORTIONAL TO THE POWER RADIATED TO THE GROUND (outer space detonation)



SOURCE: Miller and Passell (1963)

Figure A-16

APPROXIMATION OF OUTER SPACE THERMAL PULSE TO SEA-LEVEL AIR BURST



SOURCE: Stanford Research Institute

Although at first glance the results for very high altitude shots may appear to be inconsistent with those for outer space, they actually are quite consistent. In Figure A-17, the thermal pulse from a very high altitude shot is compared with one detonated in outer space. The high altitude shot shows a very high pulse in an extremely short interval, followed by a long, slowly decaying tail. The outer space shot has a much reduced efficiency, loses the early, high peak, but retains the same shape as the tail of the high altitude pulse. These results are plotted on arithmetic paper in Figure A-18.

Since for outer space detonations the fireball is pancake-shaped, the thermal flux on the ground does not vary by the simple $1/R^2$ scaling. This problem has been considered in Miller and Passell (1963), and constant thermal flux contours for 100-mt and 1,000-mt weapons are shown in Figures A-19 and A-20 for various altitudes of detonation. In Figures A-21 and A-22, the power flux for 100 mt and 1,000-mt weapons are seen as a function of distance from ground zero for varying altitudes of detonation. Also plotted on these figures is the expected flux for bursts at 50 km (31 miles), using the methods developed in Miller and Passell (1963). All of these figures apply only for a very clear day. No transmittance factor has been considered.

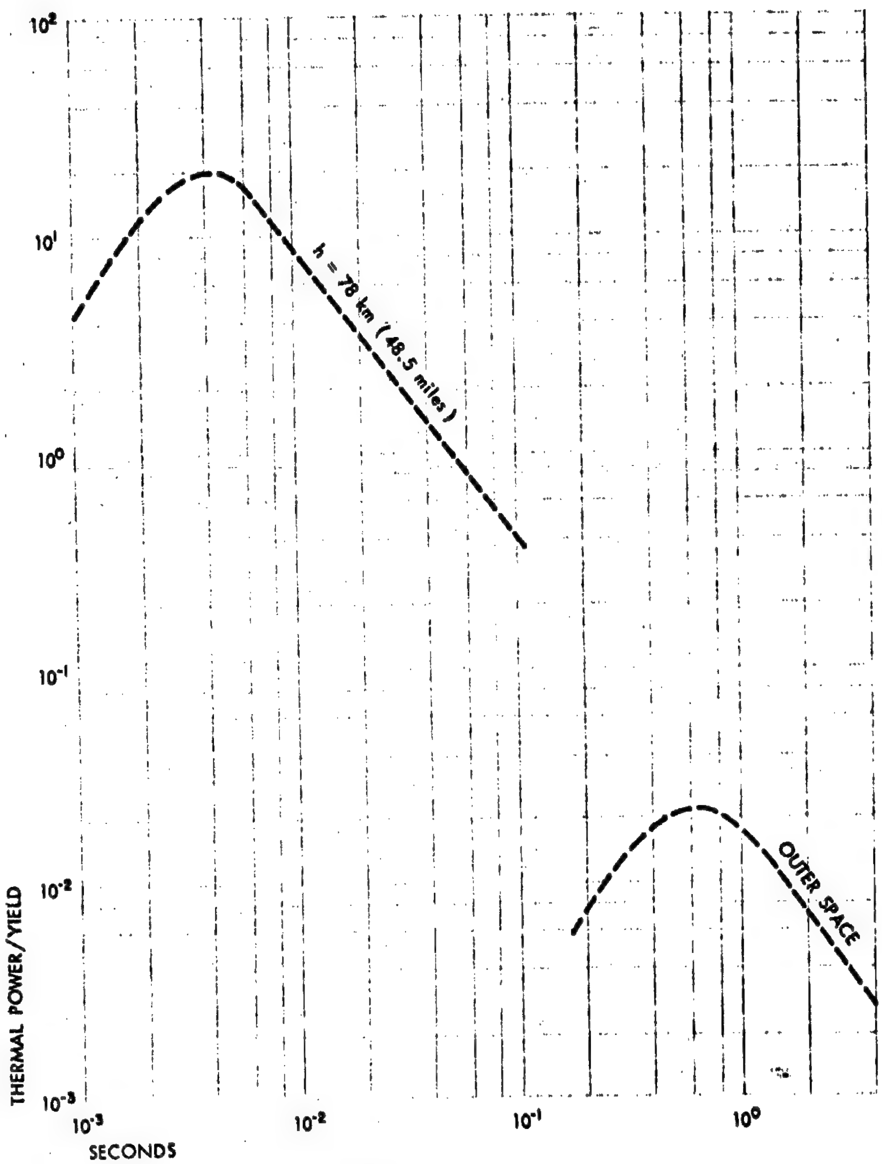
Intermediate Altitudes

If one ignores the shock wave for altitudes below about 50 km (31 miles), the theory predicts thermal pulse parameters which are not in agreement with existing data. The atmosphere holds back the energy, causing the peak power to occur at a much later time and with less amplitude.

Classified information on the pulse shape at intermediate altitudes has been deleted.

Figure A-17

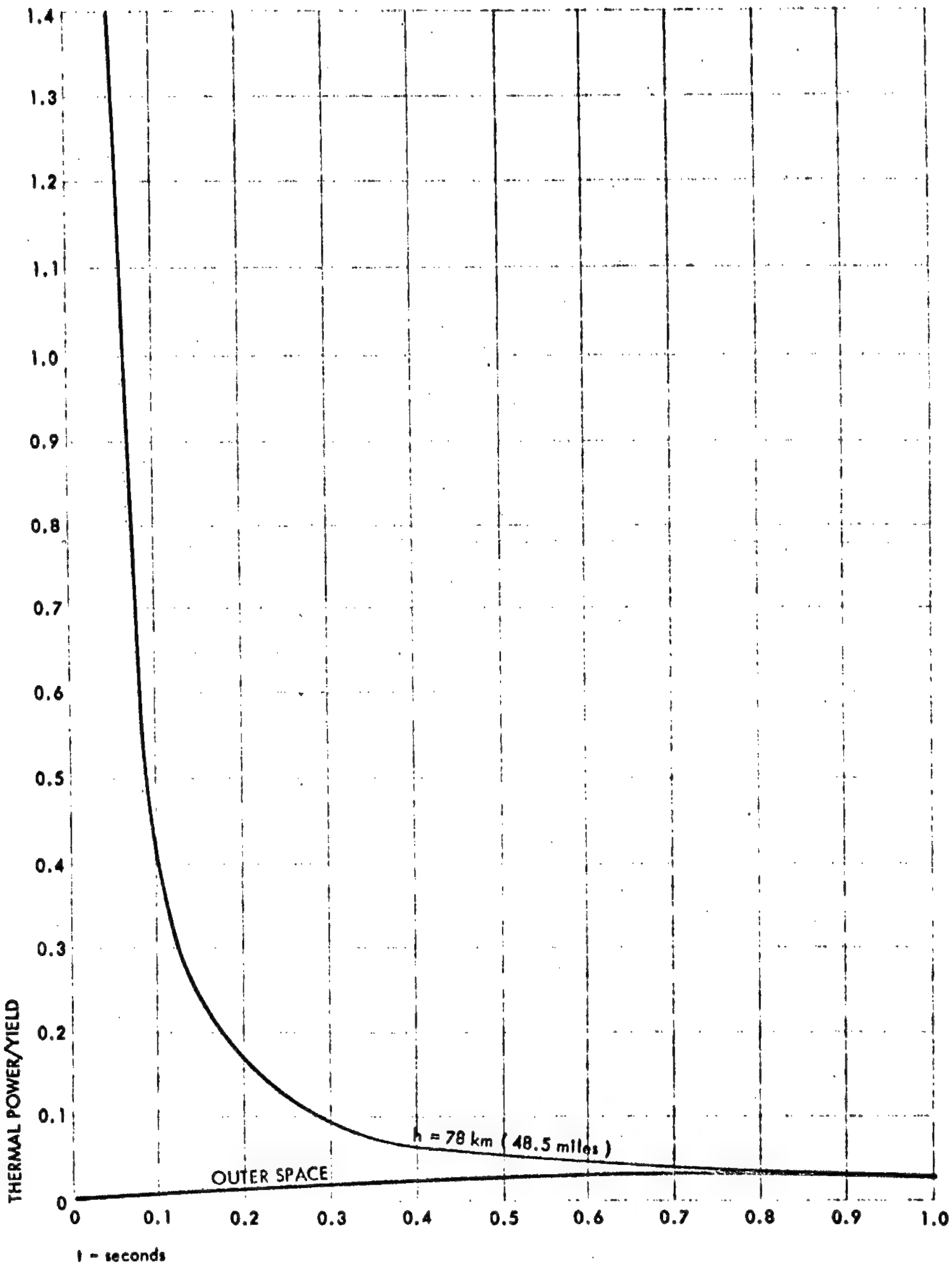
LOGARITHMIC COMPARISON OF THERMAL PULSE OF VERY HIGH ALTITUDE AND OUTER SPACE DETONATIONS



SOURCE: Stanford Research Institute

Figure A-18

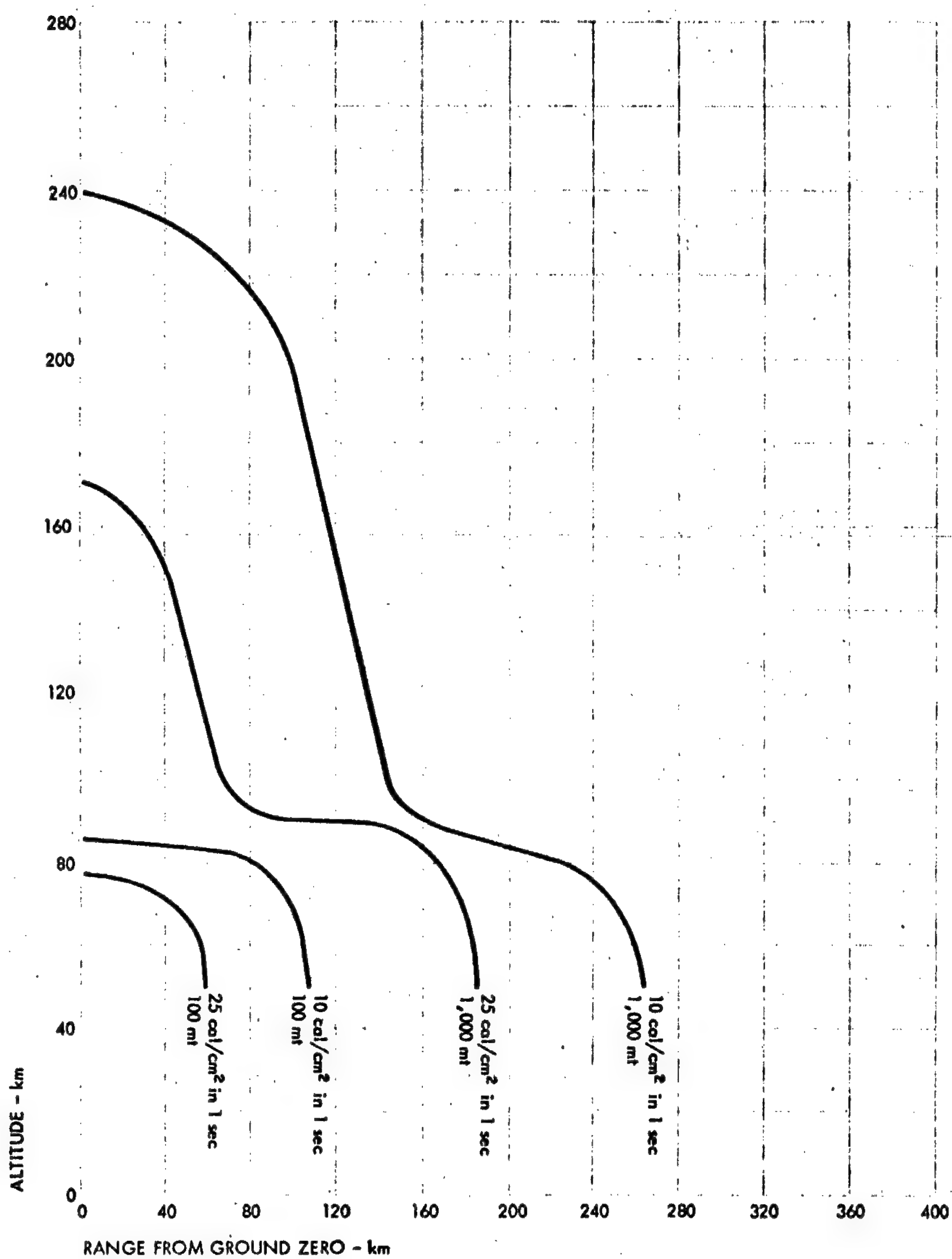
ARITHMETIC COMPARISON OF THERMAL PULSE OF VERY HIGH ALTITUDE AND OUTER SPACE DETONATIONS



SOURCE: Stanford Research Institute

Figure A-19

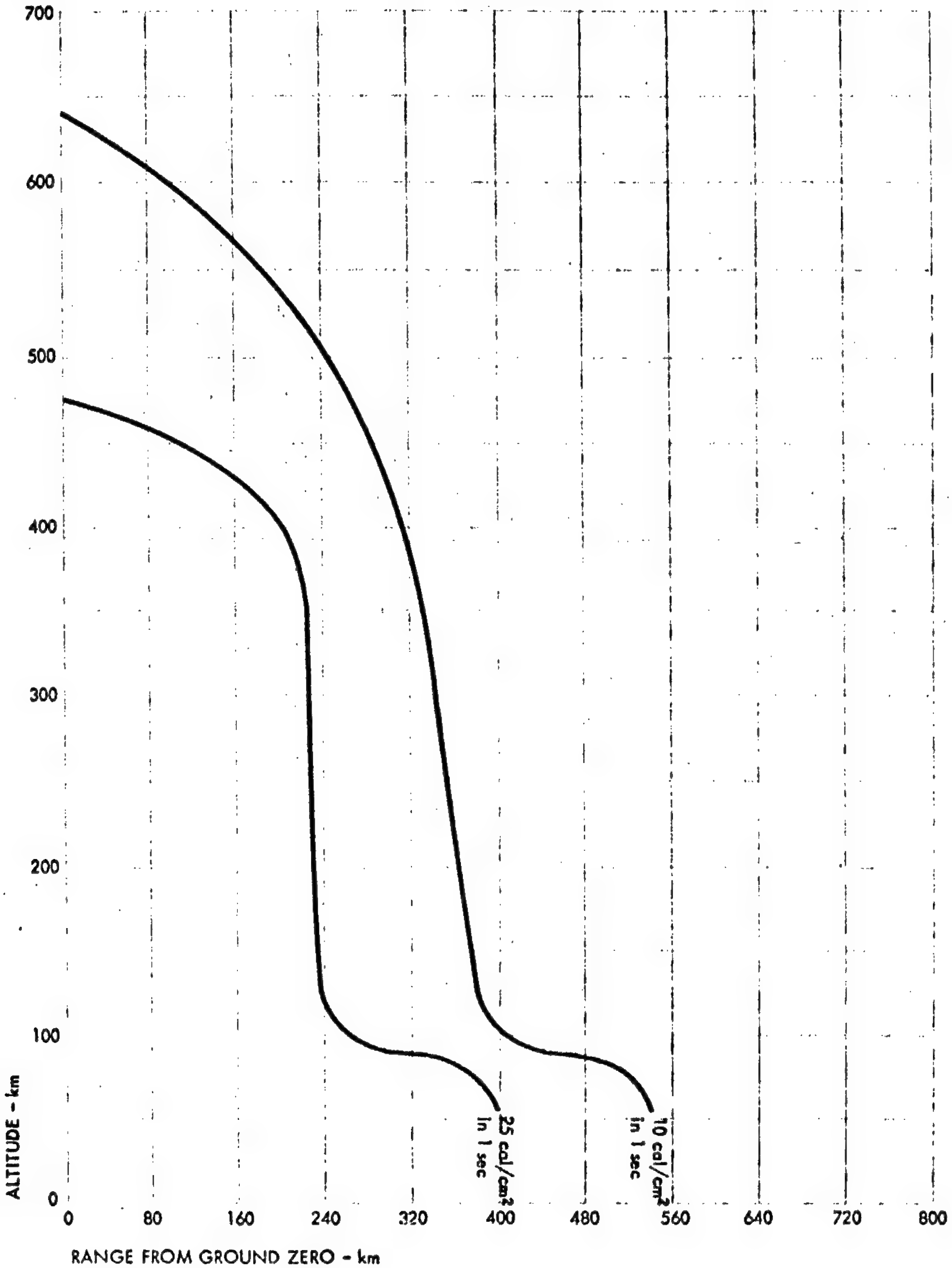
RANGE FOR TWO ENERGY FLUX LEVELS AS A FUNCTION OF ALTITUDE (100 and 1,000 mt)



SOURCE: Passell (1963)

Figure A-20

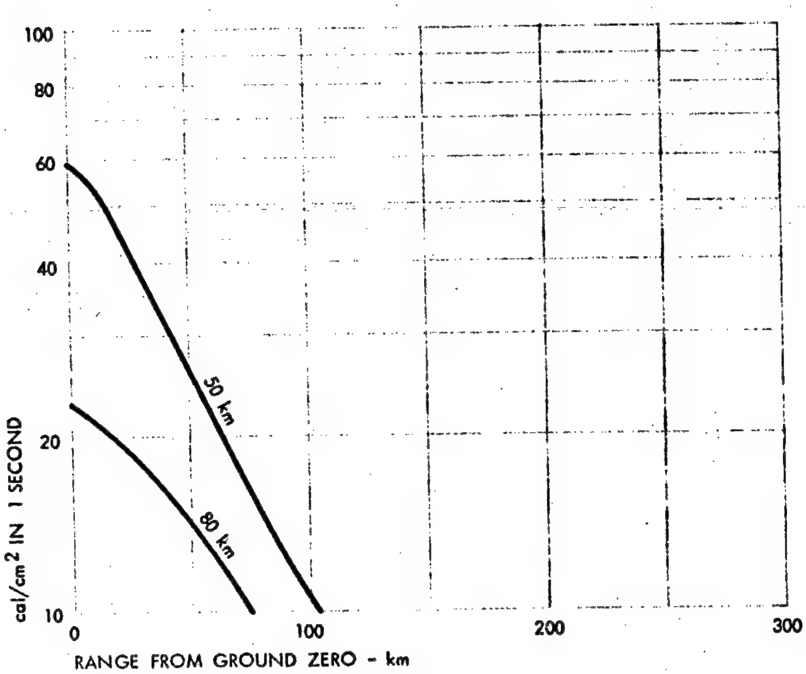
RANGE FOR TWO ENERGY FLUX LEVELS AS A FUNCTION OF ALTITUDE (10,000 mt)



SOURCE: Passell (1963)

Figure A-21

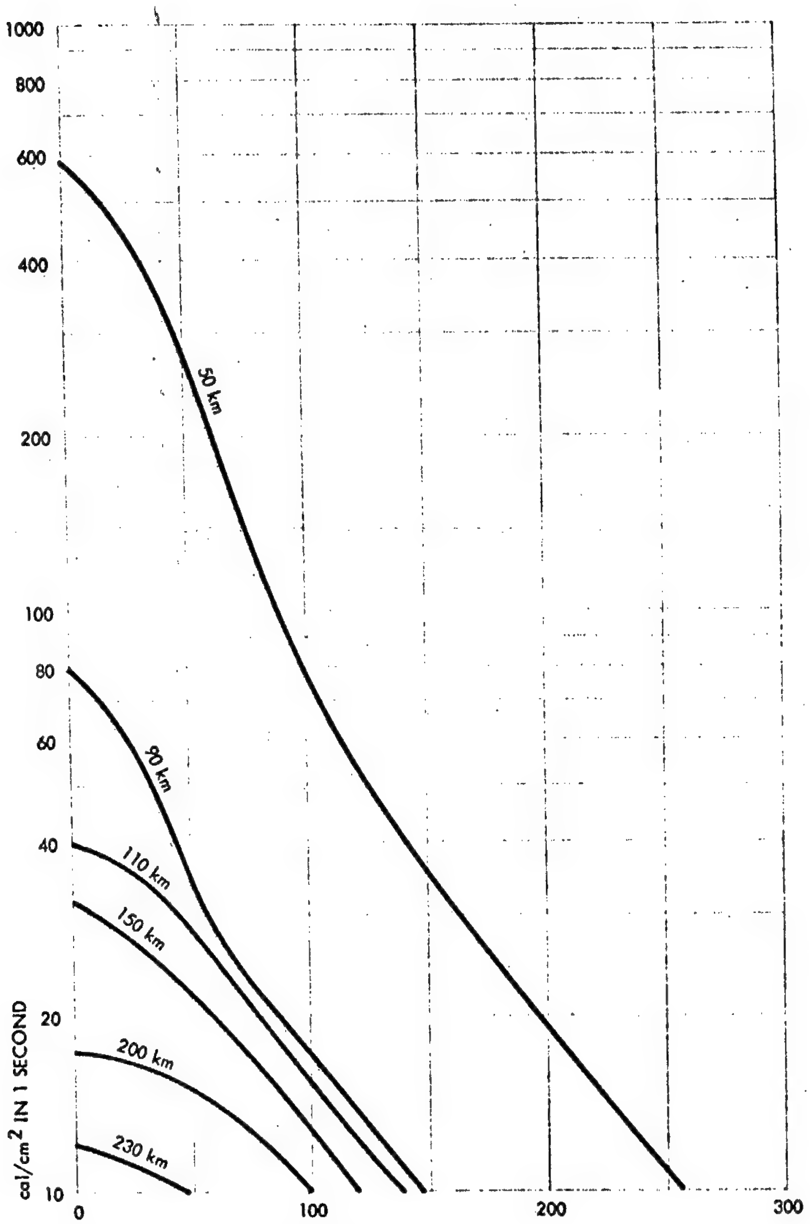
ENERGY FLUX FROM 100 mt DEVICE ON OPTIMALLY ORIENTED SURFACE



SOURCE: Passell (1963)

Figure A-22

ENERGY FLUX FROM 1,000 mt DEVICE ON OPTIMALLY ORIENTED SURFACE



SOURCE: Passell (1963)

Classified Figure A-23 on scaling of time and power with air density has been deleted.

In Figure A-23 the peak power of the test shots is also plotted, scaled with yield as at sea level, and shown as a function of air density. The data are not well represented by a simple power function of air density. Part of the problem arises in attempting to identify the peak power since it does not necessarily occur at the point of final maximum. From the above, it can be seen that the understanding of the thermal pulse shape at altitudes up to about 50 km (31 miles) is not too great.

Timing

The enemy's choice of the time of attack will greatly influence the fire potential of the nuclear weapons. A broad summary of some of the important factors affected by the timing is contained in Table A-II.

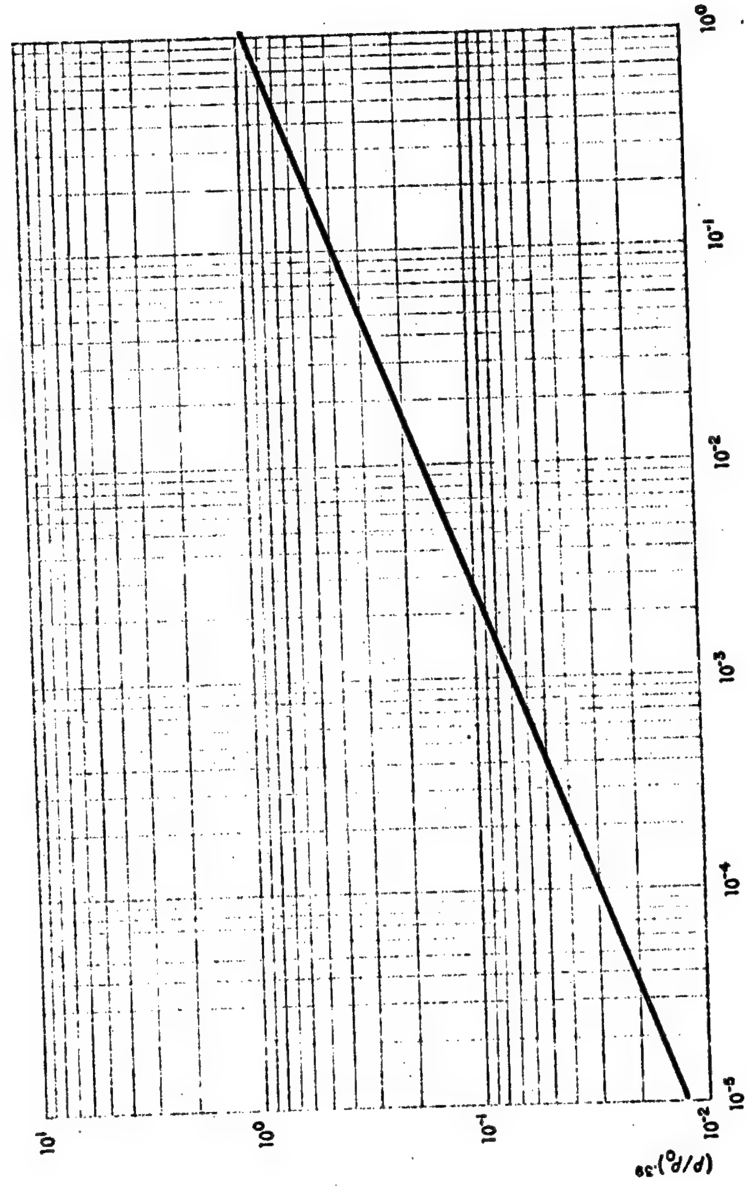
Table A-II

FACTORS AFFECTED BY TIMING OF THE ATTACK

Time Variable	Factor
Year	Enemy capabilities Countermeasures
Season	Climate, weather Vulnerability of the target
Daytime-nighttime	Weather, microclimatology Target vulnerability Countermeasures

Source: Stanford Research Institute.

Figure A-24
ALTITUDE SCALING FOR t_{max}



SOURCE: Stanford Research Institute

Year

As was pointed out earlier, the growth of weapon technology is important to the fire potential of an attack. In time, multiple warheads may be common; salvo capabilities may be realized; and thrust requirements may be no obstacle to a 1,000-mt or greater weapon. In a similar fashion, the United States may have adequate AICBM's in time, may have an aggressive shelter program, or may have means of protection by smoke screens or other countermeasures. The growth of technology is obvious and will not be discussed further. However, it should be remembered that a statement of the time frame of reference should be considered along with any estimate of a fire threat to the United States.

Season

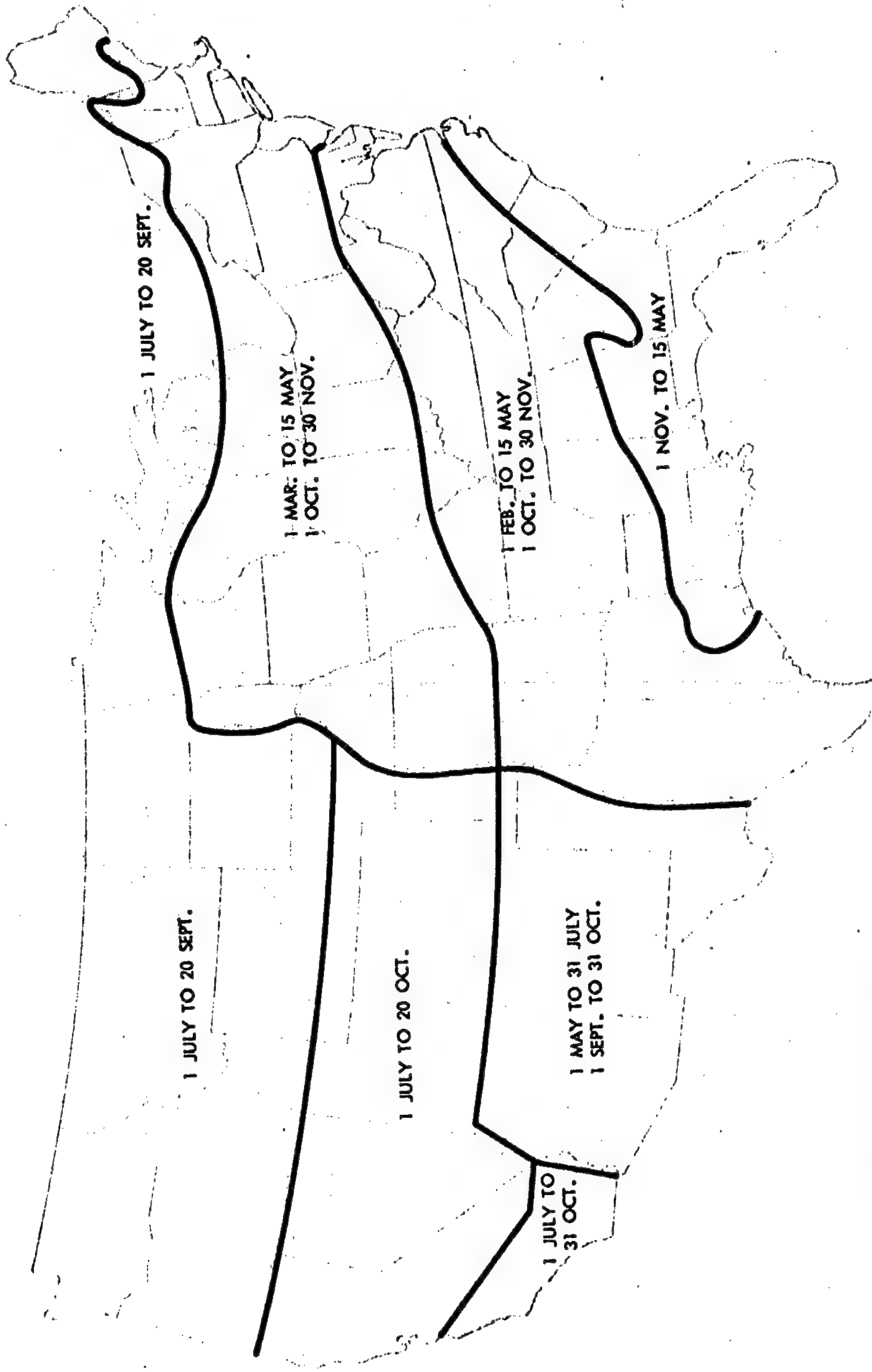
Considerable effort has been and is being spent on the seasonal variations of climate and their influence on the vulnerability of materials to ignition and fire spread. The results will be reviewed under the section concerned with the direct effects of weather on fire processes. No attention at all has been directed to the simultaneous vulnerability of all United States targets as a function of season. This fact was first pointed out by Dr. Jerald Hill in "Civil Defense...1961." In addition, the seasonal variation of climate and weather will greatly influence the amount of thermal energy transmitted to the ground from a nuclear detonation. This effect also has not been considered in the past; it will be reviewed under the section concerned with the effects of weather on the transmission of the thermal pulse energy to the target.

Figure A-25 is a map of the United States divided into regions determined by the seasons of greatest fire threat; Figure A-26 presents the same data in a slightly different form. Both figures show that at no time of the year is maximum fire vulnerability to peacetime forest fires experienced simultaneously in all regions of the United States and that the month in which the greatest number of regions are vulnerable is October. It is important to keep in mind that the map is based on forest fire statistics and does not apply to urban areas, which may differ considerably. For example, during the winter when forest may not be vulnerable to fire, building interiors may be very dry, overheated, and vulnerable.

The seasonal variation of urban fires has been treated in Pirsko and Fons (1956), a study of the number of fire starts within structures. The study shows that the frequency of fire starts in urban

Figure A-25

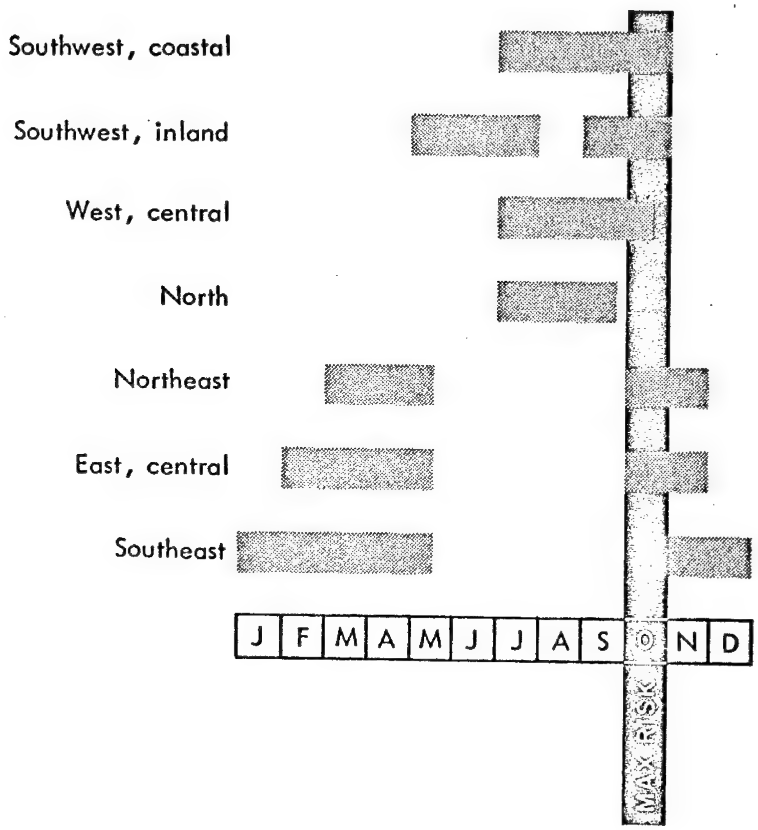
MAP OF FIRE SEASONS IN THE UNITED STATES



SOURCE: Fire Effects of Bombing Attacks (1959)

Figure A-26

FIRE SEASONS IN THE UNITED STATES



SOURCE: Based on Fire Effects of Bombing Attacks (1959)

buildings is related inversely to the moisture content of interior fine fuels as determined by outside relative humidity in summer and dew-point temperature in winter. Data on the moisture content of interior fine fuels are given in Table A-III. The assumption was made for the study that artificial heating would be employed when the interior temperature fell below 65°F and that above this temperature the air was free to circulate through open doors and windows. Figure A-27 shows the results of the study for four cities--Baltimore and Boston and the twin cities, Minneapolis-St. Paul.

The variation of temperature and humidity by season throughout the United States can be found in Visher (1954). Marvin (1941) relates these variables to the dew-point temperature. Figure A-28 gives an example of dew-point temperature as a function of relative humidity. Moreover, dew-point temperature in the morning has been found to be very closely correlated to the minimum temperature of the previous night. This relationship is shown in Figure A-29.

As a point of interest, data for the moisture content of heavy interior and exterior fuels (such as porches and interior woodwork) have been extensively analyzed in Peck (1932). As a sample, an average for the moisture content of interior woodwork is shown in Figure A-30.

In fine fuels, however, moisture contents change much more rapidly. Actually, once the moisture content of the fine fuels has been established, its effect on the ignition of the material from a nuclear thermal flash is quite well understood, as will be seen later.

The above conclusions apply only in a limited way to the fire potential of nuclear weapons. Obviously, ignitions which occur outside buildings are critically dependent on a different set of variables. Once a mass fire is started, its spread is dependent on winds, other climatological factors, and the distribution and condition of heavier fuels. Furthermore, the above data were collected only for eastern and midwestern cities--localities where overheated rooms and malfunctioning heating systems would be most common. The results of Peck's study would probably apply only to (1) the ignition of fine interior materials by the initial thermal pulse through windows or (2) to secondary ignitions from overturned stoves, broken electrical wires, and other blast effects. Even in these cases, a correlation is established rather than actual predictive laws.

It is of interest here to mention the results of fire statistics collected in Japan. In "A Survey of Fire Research in Japan" T. Kinbara (1961) reports:

Table A-III

ESTIMATE OF EQUILIBRIUM MOISTURE CONTENT OF INTERIOR FINE FUELS[a]

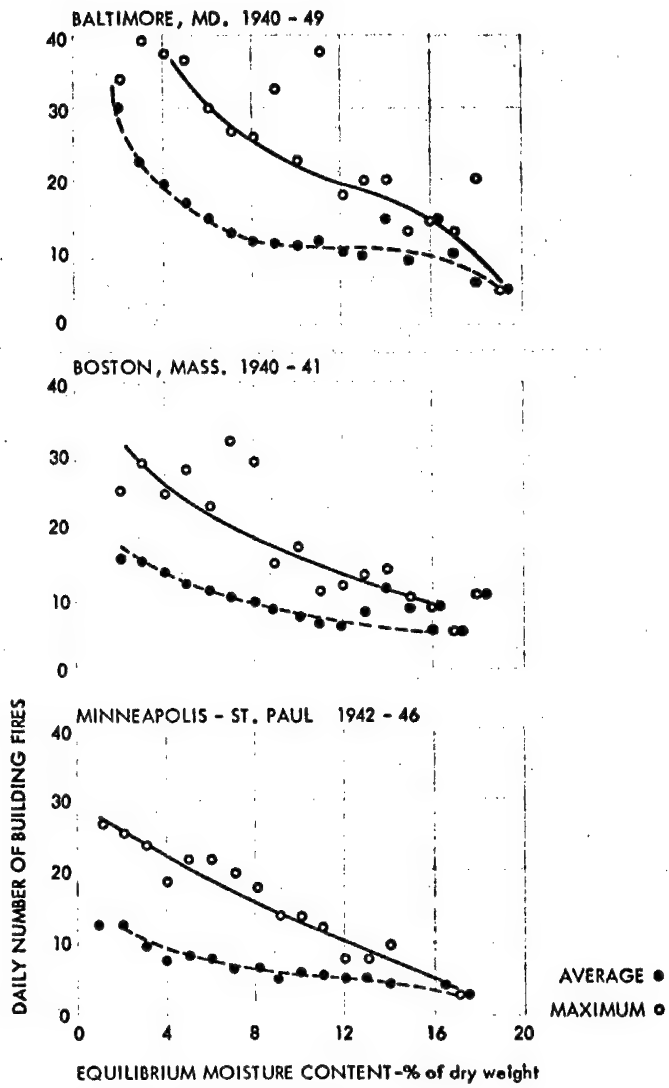
Relative Humidity (percent)	Dew-point Temperature (degrees F)	Fine Fuel Moisture Content (percent)
2% or less	-18°F or less	1%
3- 7	-17 to +2	2
8-13	3-15	3
14-21	16-25	4
22-30	26-34	5
31-39	35-40	6
40-48	41-46	7
49-56	47-50	8
57-64	51-53	9
65-71	54-55	10
72-76	56-57	11
77-81	58-59	12
82-84	60-61	13
85-88	62	14
89-91	63	15
92-93	64	16
94-95	65	17
96-97		18
98-99		19
100		20

a. Use exterior dew-point temperatures when daily mean air temperature is 64°F or below and relative humidity when daily mean air temperatures are 65°F or above.

Source: Pirsko and Fons (1956).

Figure A-27

RELATIONSHIP OF DAILY NUMBER OF BUILDING FIRES AND EQUILIBRIUM MOISTURE CONTENT OF INTERIOR FINE FUELS IN THREE U S CITIES



SOURCE: Pirsko and Fons (1956)

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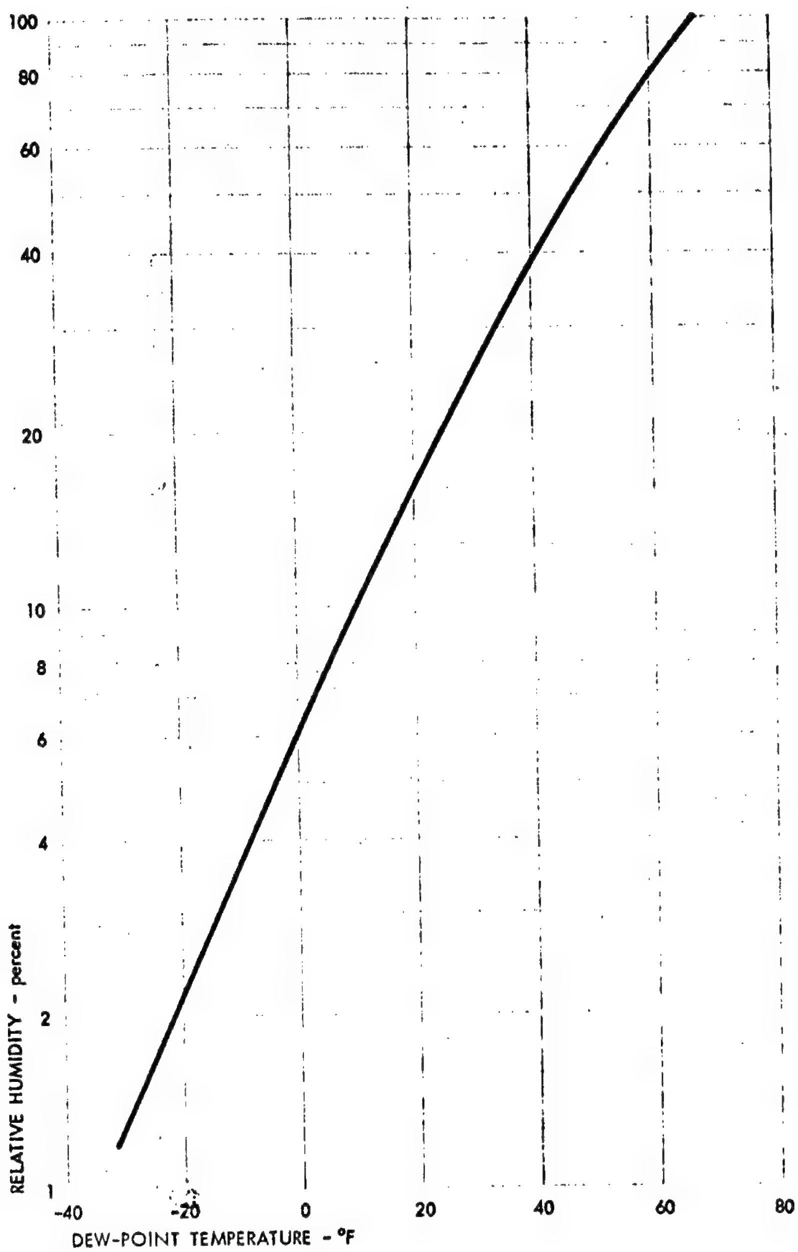
Figure A-28

RELATIONSHIP OF DEW-POINT TEMPERATURES TO RELATIVE HUMIDITIES AT 65° F



SOURCE: Pirsko and Fons (1956)

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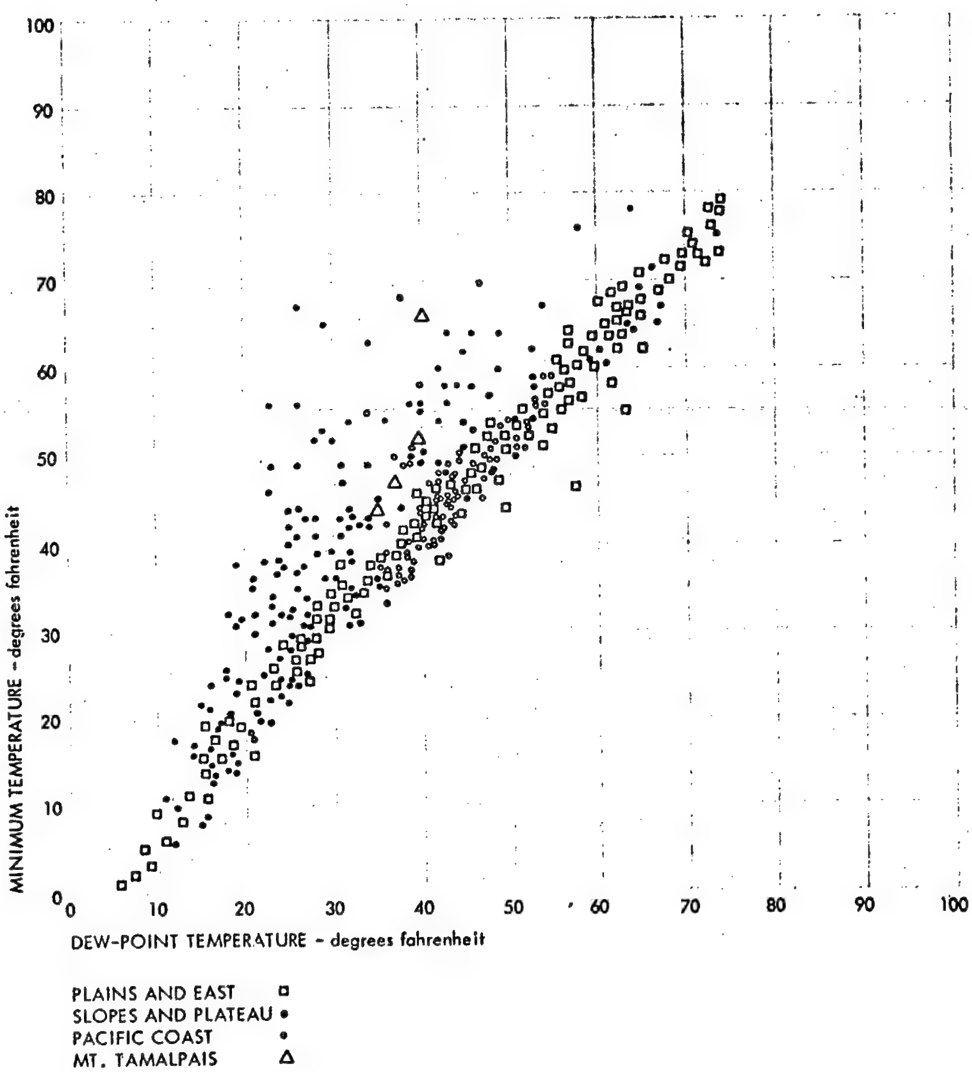
Figure A-29

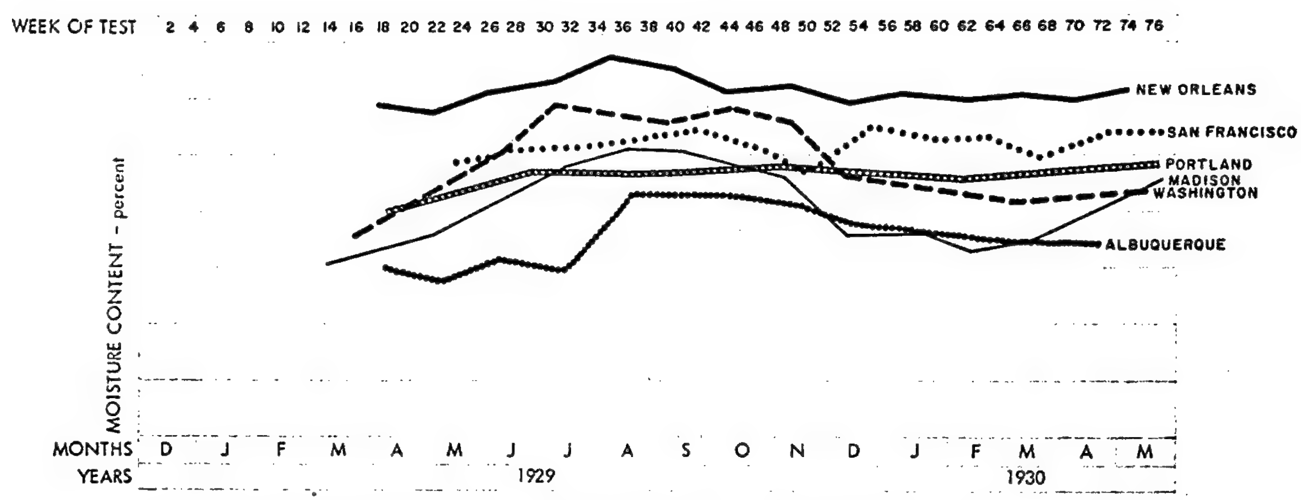
DEW-POINT TEMPERATURE VS MINIMUM NIGHTTIME TEMPERATURE



SOURCE: Gentilli (1955)

Figure A-30

MOISTURE CONTENT OF WOOD IN DWELLINGS



NOTE: The average moisture content for the principal interior woodwork in houses throughout the United States is about 9 percent, except in arid regions and in warm, damp, coastal areas, according to this graph, which is based on the average moisture content of shellacked maple blocks in the "living" part of houses studied in six widely separated cities

SOURCE Peck (1932)

"A characteristic seen in the fires in Japan is that the frequency of their outbreak depends greatly upon the season. In the case of the Edo (Tokyo) fires, they broke out as many as 61 times during the winter season of December through March, while only two times during the summer season of June through September. The statistics of Tokyo fires in recent years show that the monthly outbreaks of fire during December through March number roughly 500 times, while only about 300 times during June through September. Two reasons for this are considered. The first reason is that heat is used more frequently in winter than in summer. The second is that materials such as wood, paper, fiber, etc. are more easily ignited in winter than in summer because the wind is stronger and the air is less moist in winter. The mean humidity of Tokyo is 60 percent in winter and 80 percent in summer."

In considering the effects of humidity, the Japanese have defined a quantity known as the "effective humidity." This is an index in which the humidity of previous days is also taken into effect. It is the weighted mean of the humidities of today, yesterday, the day before yesterday, etc., with the weights of 1, r, r^2, and so on. Hatakeyama (1943) found statistically that when all fires were counted no matter how small, the number of daily outbreaks had a closer relation to the mean humidity of that day. When only those fires which destroyed more than half a house were counted, the number of daily outbreaks had a closer relation with the effective humidity for $r = 0.7$. The effective humidity factor is now used by authorities in Japan for fire warnings. These results indicate that the moisture content of heavy fuels is more important than that of fine fuels in serious fires since the heavy fuels respond more slowly to humidity changes. The effective humidity, as defined by the Japanese, has apparently never been used in fire research in the United States.

So far, only the seasonal variation of the vulnerability of material has been considered. Obviously, the season will also affect the care of refugees in the post-attack period. Severity of the climate may greatly influence the number of casualties or deaths that might occur.

In summary, there have been some attempts to study the direct relation of the season of the year to the peacetime threat of fires. Other attempts are being made to link intermediate factors of weather and climate with the ignition behavior of fires since weather is a well

known function of season. These studies will be considered later. In wartime, two additional effects of weather are (1) the modification of the nuclear thermal pulse (which will also be reviewed later) and (2) the vulnerability of the population.

Daytime-Nighttime

The attenuation of the thermal pulse by the atmosphere will be affected by the time of day, as well as by the geographic location of the target.* Weather and microclimatology are also affected by the time of day. The velocity of winds normally becomes higher in the afternoon; the direction of the winds are time-dependent; materials may become more vulnerable due to preheating of the sun; humidity changes may be important to fine fuels; time-dependent inversions may affect transmittance of the atmosphere and the feasibility of smoke clouds generated as countermeasures; and so on.

In reference to forest fires, it has been found that "fires of all sizes and intensities are most likely to occur, or at least originate, during the middle of the afternoon on sunny days. This is the time of the day that fuel flammability is highest. It is also the time of day when thermal turbulence in the lower atmosphere is at a maximum," Davis (1959). The Japanese have found that forest and prairie fires break out by an overwhelming majority between 11 a.m. and 2 p.m., the period when the air is most dry. This agrees quite well with the urban conflagrations of Tokyo, most of which started between noon and 4 p.m.; see Suzuki (1928) and Kinbara (1961).

Figure A-31 shows an example of the variation of the humidity and temperature at two weather stations near a large (17,000 acres) forest fire, Chandler (1961). Clearly, the afternoon is the most critical for fires since the moisture content and initial heating of the materials are fairly responsive to ambient humidity and temperature changes.

In the mountainous areas the winds vary in a regular pattern with the time of day, beginning with light upslope winds and strong down-canyon winds at sunrise and with the direction and magnitude of the resultant slope-canyon wind developing as in Figure A-32. It was observed by the author that the rate and direction of fire spread in the Basin Fire, July 13-22, 1961, seemed to follow closely this standard resultant vector

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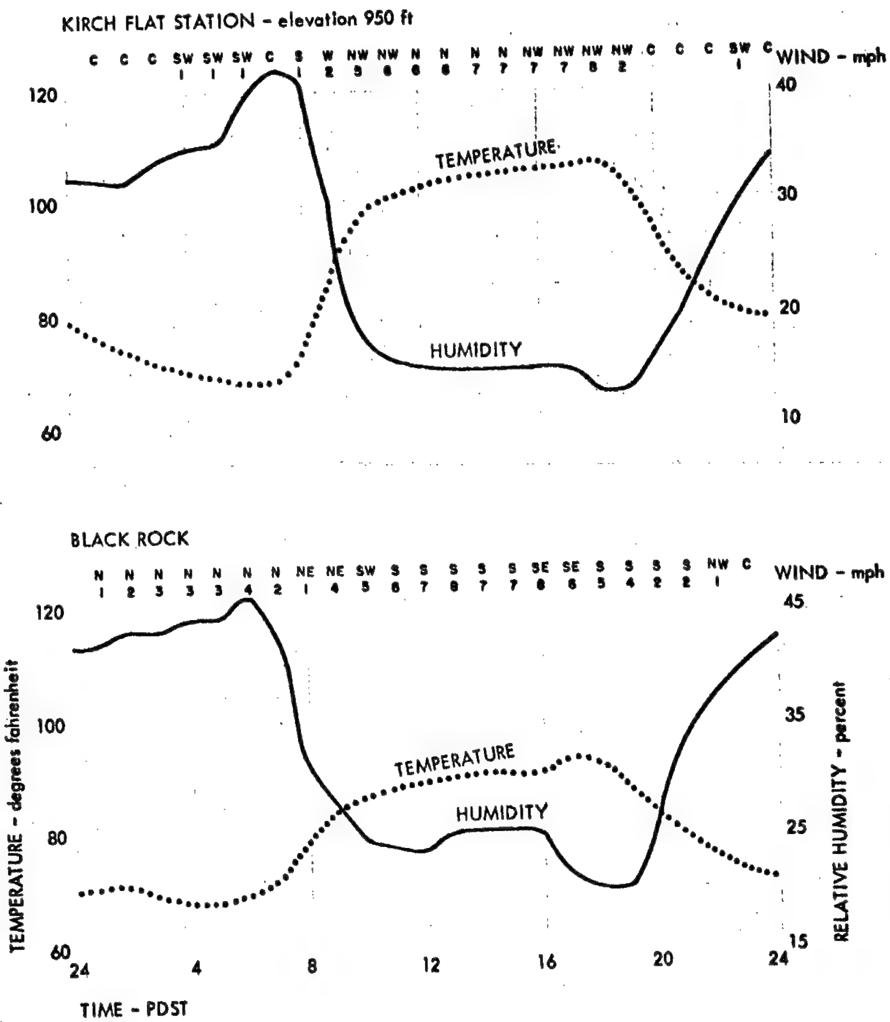
* See Figure C-8.

Figure A-31

TYPICAL DAILY TEMPERATURE, HUMIDITY, AND WIND CYCLES

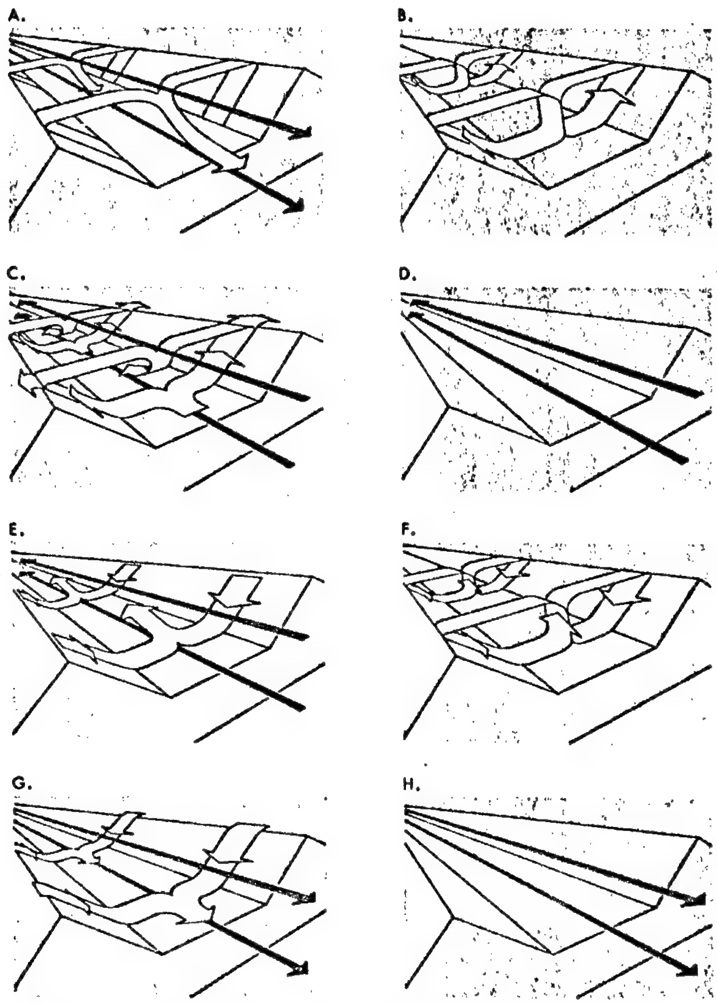


NOTE: Winds are 60 minute averages. At Kirch Flat site, N is upcanyon, S is downcanyon. At Black Rock site, S is upslope, N is downslope.

SOURCE: Chandler (1961)

Figure A-32

SCHEMATIC ILLUSTRATION OF NORMAL DIURNAL VARIATION OF THE AIR CURRENTS IN A VALLEY



NOTE:
A. Sunrise; beginning of upslope winds (white arrows), continuation of mountain wind (black arrows).
B. Forenoon (about 0900); strong upslope winds, transition from mountain wind to valley wind.
C. Noon and early afternoon; diminishing slope winds, fully developed valley wind.
D. Late afternoon; slope winds have ceased, valley wind continues.
E. Evening; onset of downslope winds, diminishing valley wind.
F. Early night; well-developed downslope winds; transition from valley wind to mountain wind.
G. Middle of night; downslope winds continue, mountain wind fully developed.
H. Late night to morning; downslope winds have ceased; mountain wind fills valley.

SOURCE: Davis (1959)

wind. If this is true, then at any point on the fire front one could draw a coordinate system with one axis upslope and the other upcanyon. In this system, the rate and direction of fire movement could be analytically related to the time of day. The hypothesis was tested, making use of the daily fire maps. It was found on a topographical map that the fire spread was closely related to the wind vector, although fires progressed upslope somewhat faster, presumably because of the proximity of the flames to the ground.

A similar study was made of the Woodwardia Fire, Chandler (1960). In this case, the correlation of fire direction and rate of movement with hypothetical slope and canyon winds was not so clear. This was undoubtedly due to strong winds developing from the Los Angeles Basin. Time did not permit a further analysis of the data.

The direct relationship of existing winds to fire spread and development will be considered later, without regard to their relationship to the time of day.

The preheating of ignitable fuels by solar radiation can greatly affect the rate of spread of fires. A classic experiment was conducted in 1946 to test the spread of fire in light forest fuels, Fons (1946). In this experiment, a uniform bed of upright twigs was ignited in a wind tunnel. A theory was developed for the rate of spread of the fire as a function of the wind velocity, fuel temperature, fuel moisture content, fuel surface-volume ratio, and fuel spacing. The results showed a very close agreement with the theory. The effect of initial fuel temperature is quoted below.

> "An increased fuel temperature from 70° to 120°F causes a net increase of 29.5 percent in fire spread . . . . A larger increase in spread results with rising wind velocity for a given temperature change; i.e., for the same conditions as above except that with the wind velocity at 10 mph, a rise in temperature from 70° to 120°F produces a 94 percent increase in rate of spread. The tendency of a fire to slow down soon after a shadow from a cloud is cast on the fuel ahead of the fire has frequently been observed. The fuel temperature in the rate-of-spread equation offers a possible explanation of this phenomenon, since fine fuels in complete shade soon assume air-temperature conditions, while in direct sunlight a much higher fuel temperature generally prevails."[1]

1. Fons (1946).

Geiger (1950) contains examples of the rise in temperature in light fuels as a function of time of day. Figure A-33 shows that plants can easily vary by 40°C (72°F) over the period of a day, so that preheating by the sun can be quite important. Even solid fuels will experience significant temperature changes from solar radiation. It has been found, for example, that the various exposures of a tree trunk are related in amount and time of their maximum temperature values in the same way as are the corresponding slopes of a circular hill. The shady north side receives its heat in the main only from the surrounding air--by conduction, not by radiation. Furthermore, the penetration of heat from the bark into the interior of a tree does not differ essentially from the penetration of daily temperature fluctuations from the earth's surface into its interior. Chapter 21 of Geiger's treatise describes the penetration of heat into hills of earth and sand.[1] As another example of the heating of fuels by the sun, Figure A-34 shows the change of air temperature in a pine grove. Other examples are given in Geiger (1950).

Classified paragraph on effect of time of day on population vulnerability has been deleted.

The location of the urban population shifts with the time of day, as is well known. A schematic illustration of this is given in Figure A-35. As a rough planning estimate, Civil Defense Urban Analysis indicates that about one-third of the residents of the suburbs come into a city in the daytime to work, shop, attend school, or for other purposes. If due to the growth of a city its legal limits pass through densely populated residential areas, the city will have a large proportion of its resident population living outside the city limits, and hence the daytime migration toward the city will be larger. Conversely, if the city limits include an abnormally large proportion of its resident population and the

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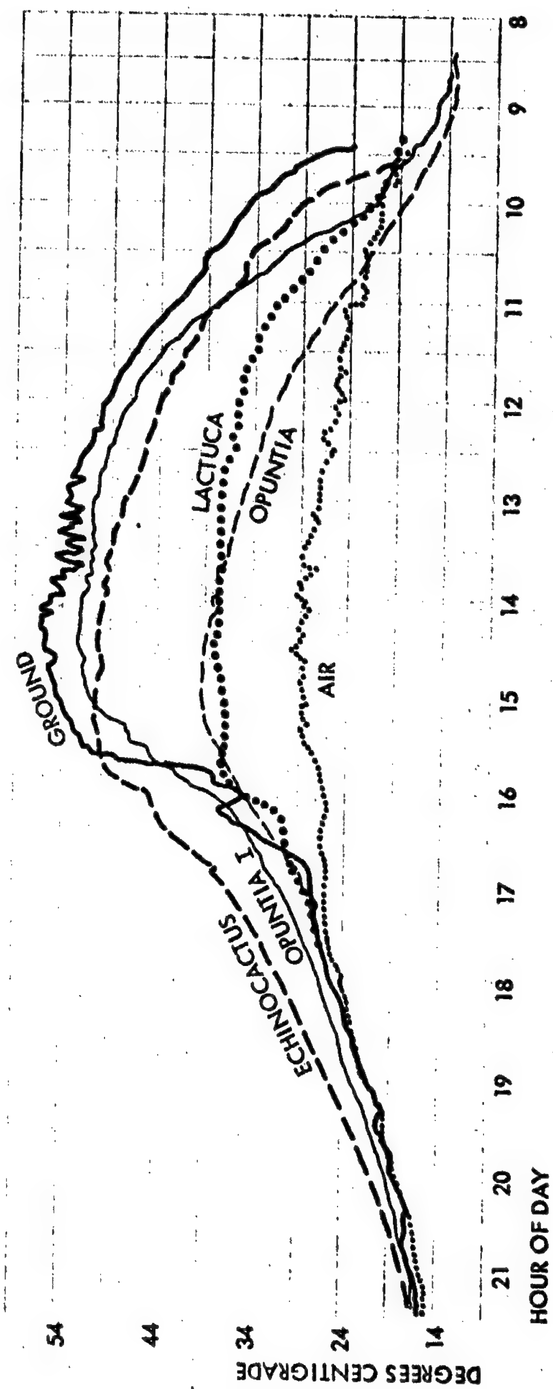
1. Geiger (1950).

Figure A-33

TEMPERATURES OF THE AIR, THE EARTH'S SURFACE, AND DIFFERENT PLANTS

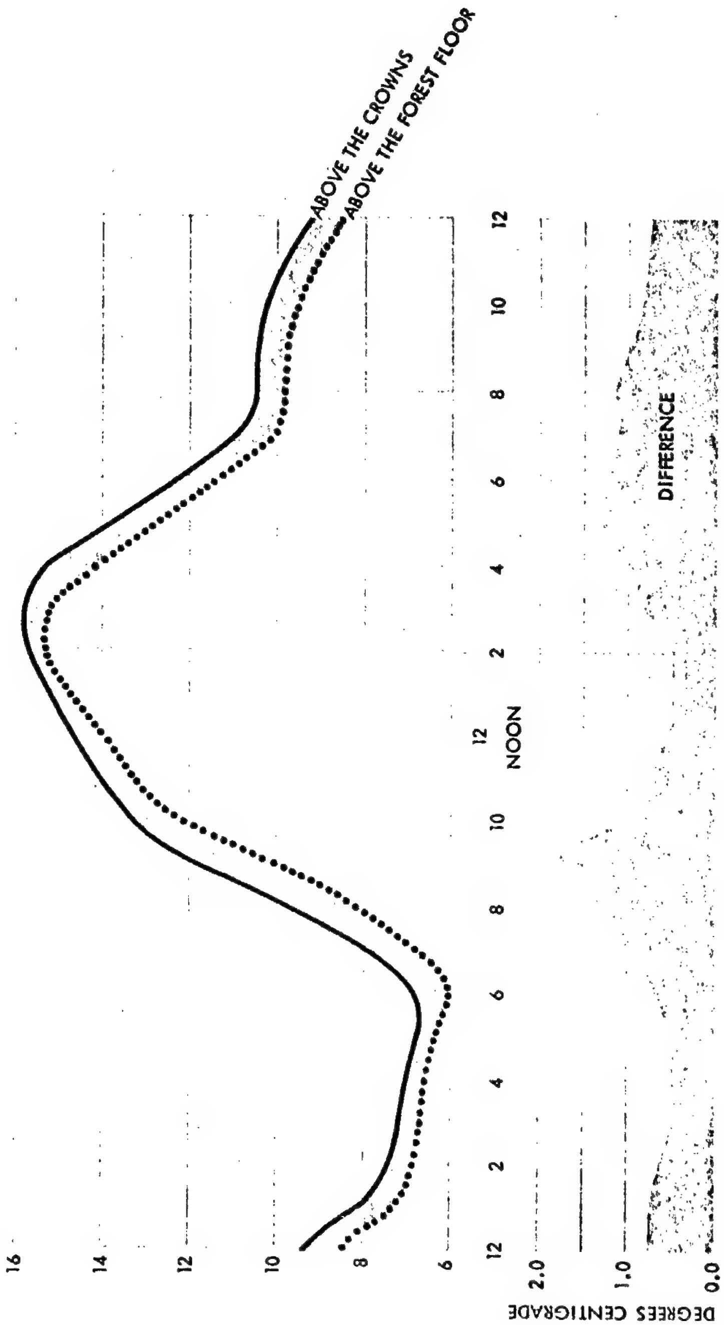
JULY 10, 1935



SOURCE: Geiger (1950)

Figure A–34

DIURNAL COURSE OF TEMPERATURE IN A PINE GROVE



SOURCE: Geiger (1950)

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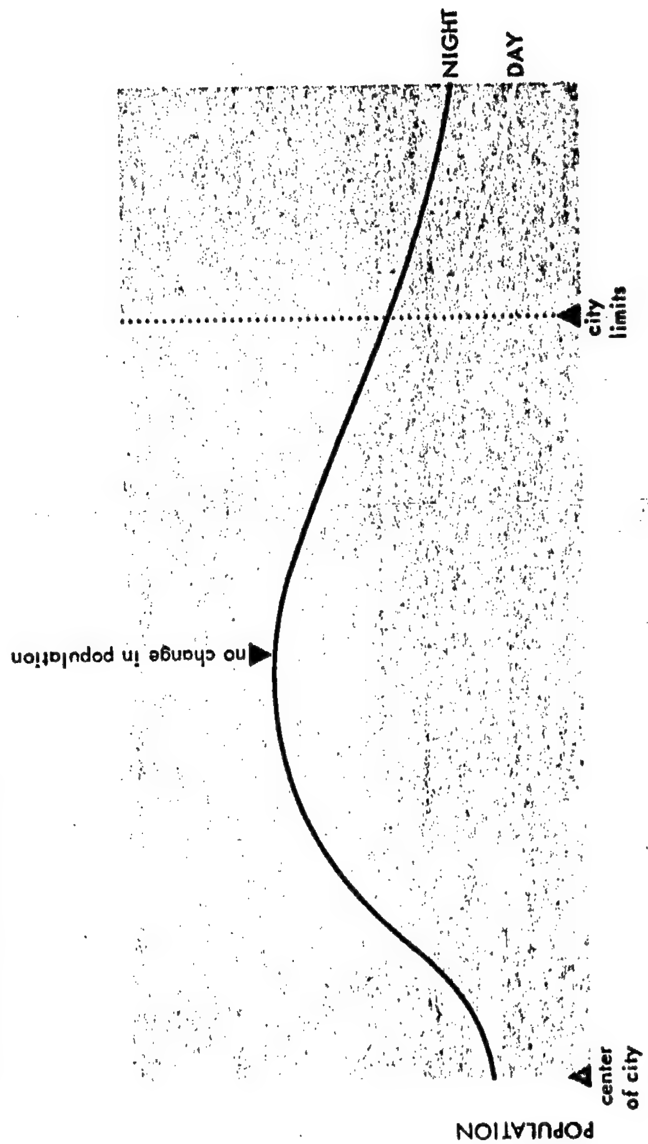
Figure A-35

POPULATION CHANGES FROM NIGHT TO DAY AS RELATED TO DISTANCE FROM CENTER OF CITY



SOURCE: <u>Civil Defense Urban Analysis</u> (1953)

outlying suburbs have well developed industries and shopping and educational facilities, the daytime migration will be less than one-third. More detailed analyses for specific cities have been done in numerous references.

As a final remark, it has been suggested that the thermal effects of weapons could be significantly attenuated by an artificial cloud of smoke or fog generated prior to the attack. The feasibility of such a countermeasure is greatly dependent upon the time of day--not only because of the variation in winds but also because of the marked change in the inversion layer as a function of daytime-nighttime. Table A-IV gives the feasibility percentages for day and night for selected cities. It can be seen from the table that feasibility is also closely related to the season. See Duckworth, et al. (1953).

Warning

The feasibility of generating a protective layer of smoke or fog as a countermeasure to thermal radiation from a nuclear detonation is clearly dependent upon warning. In the East River Project,[1] it was estimated that a maximum of one ton of oil would be required to produce particles for each square mile of protected area and that this would require a minimum of 15 minutes' warning, an optimum of 1 to 2 hours' warning.

Warning to active fire fighting forces would probably not be too important except for their own preservation since mass fires develop so quickly once started. Yoshino (1958) has analyzed, for example, the fire front shifting in the Niigata conflagration of 1955 and the Noshiro conflagration of 1956. He found that the velocity of the fire front immediately after the outbreak of fire was extraordinarily great. In the extreme case, it reached 1,670 meters per hour. Following the initial hour of burning, the velocity of the fire front decreased sharply but spread widely.

As a wartime example in Japan[2] before the city of Hachioji was attacked with incendiary bombs, it was warned of the attack by radio and leaflets. The city of Tokyo sent 50 of its largest pumper-type fire trucks and 300 professional firemen to assist the Hachioji fire

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1. See Hudgins, et al. (1952).
2. See Effects of Incendiary Bomb Attacks on Japan (1947).

Table A-IV

SEASONAL AND ANNUAL FEASIBILITY PERCENTAGES FOR DAY AND NIGHT FOR SELECTED CITIES[a]

	Winter		Spring		Summer		Fall		Annual	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
Feasibility Based on Inversion Frequencies Only										
Los Angeles	27-41	69-74	38-56	59-74	79-93	81-96	57-67	88-94	50-94	74-82
Chicago	48-62	72-90	30-53	68-79	19-35	88-90	40-55	78-84	34-51	76-88
St. Louis	48-66	68-88	31-54	65-74	25-33	85-89	81-59	73-87	36-54	74-85
New York City	29-52	53-74	5-13	60-70	6-11	64-71	8-24	57-73	12-25	60-72
Feasibility Based on Inversion Frequencies and Frequencies of Winds > 12 mph										
Los Angeles	33-47	70-75	50-65	60-74	82-94	81-98	62-72	89-94	57-70	75-85
Chicago	64-69	86-95	53-72	64-80	31-45	90-91	56-65	88-91	52-63	87-92
St. Louis	64-74	79-93	57-70	77-83	31-43	87-90	53-78	86-91	51-66	82-87
New York City	65-80	80-89	58-60	79-85	36-40	71-76	41-52	74-83	50-58	76-83

a. The left-hand figure in each column is computed for a 1,200' burst; the right-hand figure in each column is computed for a 2,000' burst.

Source: Duckworth, et al. (1953).

department. As a result, the greatest known concentration of men and equipment (55 trucks/square mile) ever gathered to fight a fire in any of the Japanese urban attacks was ready and waiting. Within 15 minutes after the attack began, a cluster of bombs hit the electric switch stations, knocking out all electric power. Public water pumps failed. The river became so low that not more than 15 fire trucks could drive onto the sand beach to get water. Houses burned, trucks caught fire, and one truck received a direct hit.

In Germany, the Hamburg firestorm was established about twenty minutes after the first bombs were dropped. The fire had run its course in about three hours, after which it began to die down; see Bond (1955). In this and other raids in Germany, it appeared that if fire crews were to be mobilized at all, the mobilization must occur roughly within a three-hour limit. Insofar as warning would help meet this limit, it would be useful.

In the United States, examples are available to show that warning is not too important to fire fighting units, except in establishing a general alertness. In the Los Angeles conflagration of 1961 described in Wilson (1962), the firemen were alerted to the high fire index of 98; a fire index is considered dangerous when it reaches 20. The fire started at 8:10 a.m., was reported by phone at 8:15, the first companies arrived before 8:18, 24 engine companies were ordered by 8:26, and so on. The reaction by the fire fighters was swift, but it was impossible to muster enough units in time to rapidly control the conflagration.

Warning is probably much more important to the individual citizen than to the active fire fighters. For one thing, retinal burns, which may occur at much greater distances than other thermal damage, will be of no consequence if people are warned not to respond to the bright flash of a fireball. With high yield weapons where the thermal pulse is sustained for a matter of seconds, a person's normal reflex to turn toward the flash would be particularly dangerous (see page C-12 and following). Flashburns on the skin could also be prevented with even the shortest warning, since merely stepping inside a house or taking shelter under an automobile would protect people from the direct rays of the bomb.

Finally, remedial countermeasures can be taken by an individual to protect his property. For example, if warning is given, a person may close the metallic venetian blinds of his home if it is so equipped. This single action would virtually ensure that no material within the home would be ignited directly by the thermal pulse.

Appendix B

INTERACTION OF THE DIRECT THERMAL RADIATION WITH OTHER WEAPON PHENOMENA, THE ATMOSPHERE, AND THE TARGET

In addition to the enemy's choice of attack strategy and tactics, there are other factors which determine the framework in which the fire potential of nuclear weapons must be considered. In this appendix, the constraints of greatest concern are those imposed by the characteristics of the direct thermal radiation, its modification by the physical environment, and its interaction with the target complex. In Appendix C, additional relationships of climatic factors and topography to target vulnerability, fires, and fire spread are considered.

The standard texts for nuclear effects are the Capabilities of Atomic Weapons (1957) and the unclassified version, The Effects of Nuclear Weapons, edited by Glasstone (1962). At the time of this writing, a new edition of the Capabilities is being assembled. For more detailed official information on thermal, blast, and radiological effects, see respectively, The Thermal Data Handbook (1954), Nuclear Weapons Blast Phenomena (1960), and Nuclear Radiation Handbook (1957).

In most studies of weapons effects, little attention has been paid to the combined effects of thermal, radiological, and blast damage. This interaction can no longer be entirely ignored in treating the fire problem. Not only does the ratio of blast to fire-damaged areas vary significantly with yield, but blast can overturn stoves, break electric wires, and in other ways start fires in addition to those caused by the initial thermal pulse. Other considerations which should be assessed include the possibility of the extinction of fires by the follow-on blast wave, the marked redistribution of radioactive particles in the vicinity of large scale fires, and the possibility of firestorms developing rapidly in blast-damaged debris.

Interactions between the Blast Wave and the Threat of Fire

Ignitions Caused by the Blast Wave

If a nuclear weapon is detonated over a target area, two possible types of fires may start. Primary ignitions are the direct result of the thermal radiation from the nuclear weapon striking and igniting kindling fuels.* Secondary ignitions, to be considered in this section, are the indirect result of the blast wave from the weapon--e.g., overturned stoves, broken gas mains, shorted electric wires, or the like.

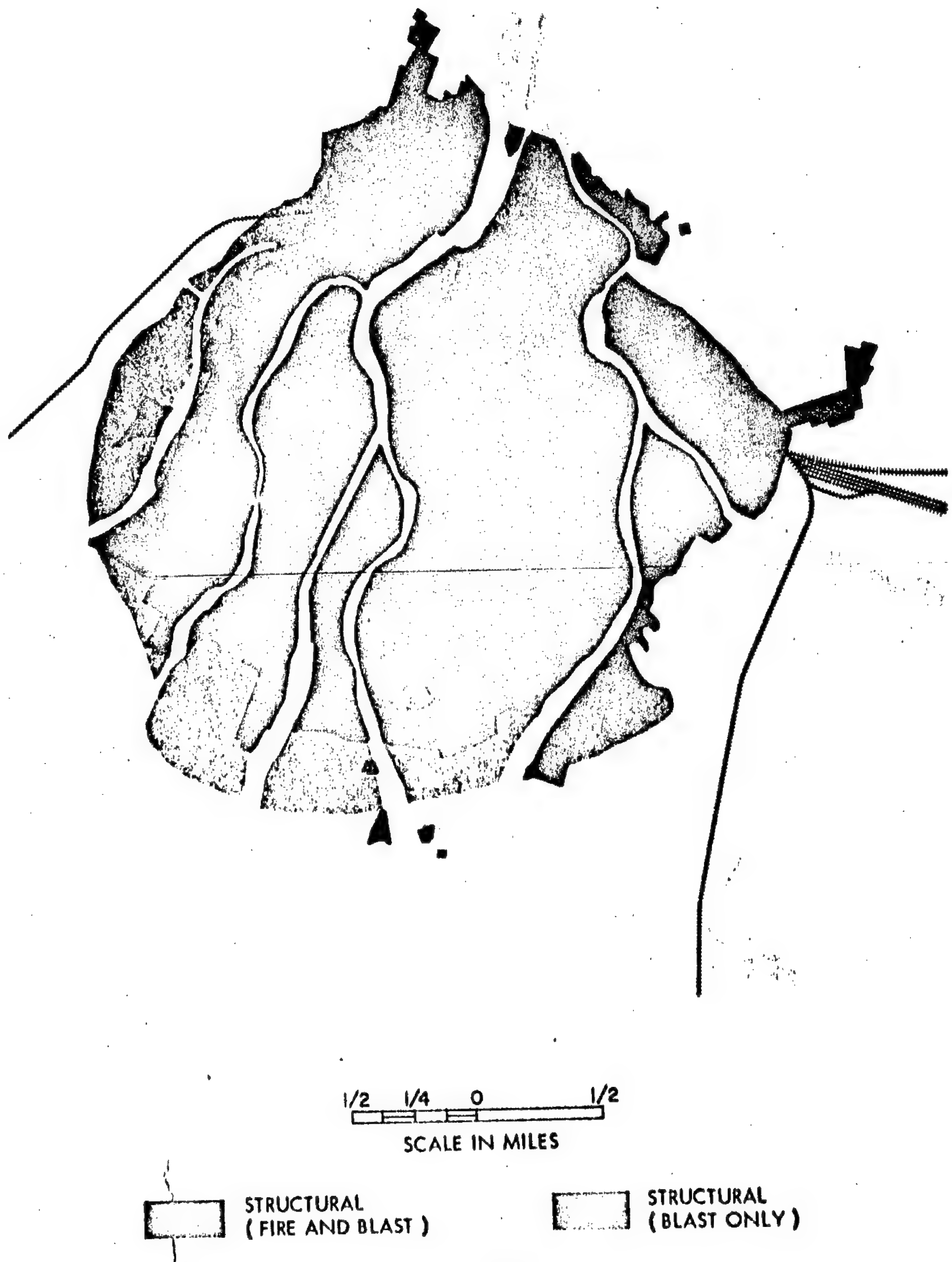
After World War II, many assessments were made of the damage caused by the atomic bombs dropped on Hiroshima and Nagasaki. The cause of fires was difficult to determine since the areas destroyed by fire and blast were essentially the same; see Figures B-1 and B-2. In fact, the British and American reports on the relative importance of primary and secondary fires were contradictory--the British stating that the primary fire was most predominant; the Americans, that the secondary fire was the principal cause of fire damage; see Brown (1962). In spite of these differences of opinion, it can be assumed that in any future attack launched on a clear day, the ratio of the number of primary fires to the number of secondary fires will be greater than it was in the atomic attacks on Japan since the thermal radiation effects cover proportionately larger areas than blast damage from the megaton yields.

Two classified paragraphs pertaining to blast wave ignitions have been deleted.

* Kindling fuels are thin materials or rotted, flaking heavy materials.

Figure B-1

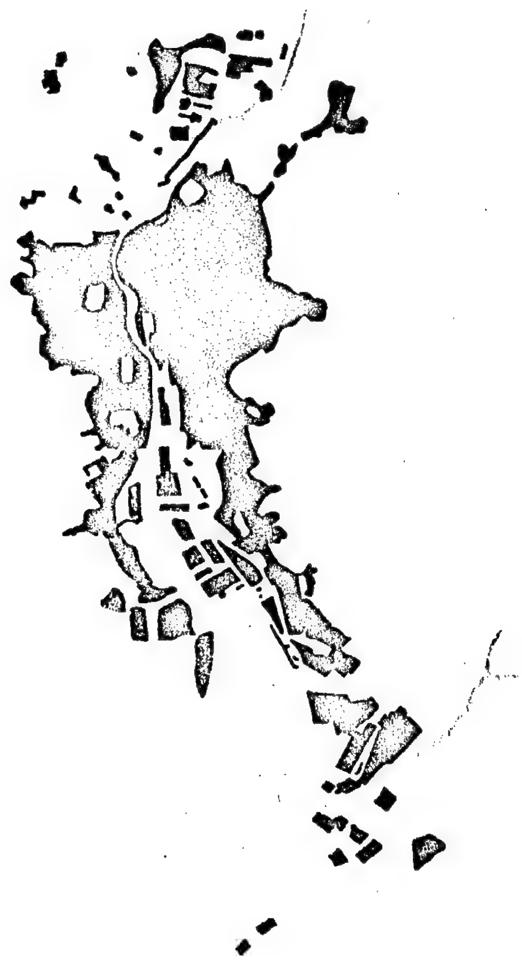
COMPARISON OF BLAST AND FIRE DAMAGE—HIROSHIMA



SOURCE: U S Strategic Bombing Survey (1947)

Figure B-2

COMPARISON OF BLAST AND FIRE DAMAGE—NAGASAKI



1/2 1/4 0 1/2

SCALE IN MILES

STRUCTURAL
(FIRE AND BLAST)

STRUCTURAL
(BLAST ONLY)

SOURCE: U S Strategic Bombing Survey (1947)

A second approach to the understanding of the relative importance of primary and secondary ignitions was made by Brown (1962) in a brief study of fires caused by earthquakes. He concludes that in Japan the number of secondary fires caused by earthquakes is important. In Fukui, out of 15,525 houses, 2,069 were destroyed by fire; in Maruoka, out of 1,760, 1,360 were destroyed by fire; and in the great Tokyo earthquake, 447,128 houses were burned (of an unknown total number).

In the United States, the history of fires caused by earthquakes is somewhat different. In the 1906 San Francisco earthquake (magnitude 8.2 on the Richter scale), a conflagration resulted from spreading of small fires which burned out of control because of the failure of the water supply. In Santa Barbara (1925--magnitude 6.25), no fires occurred. In Long Beach (1933--magnitude 6.7) and Tehachapi (1952--magnitude 7.5), fires started only in an oil field and in an oil refinery, and in neither city did the fire spread. From these data, Brown concludes that in a U.S. city it is probable that primary fire rather than secondary fire will be the major problem in the event of a nuclear weapon attack.

Extinction of Incipient Fires by the Blast Wave

In addition to the paucity of data on secondary ignitions, very little information is available on other interrelations between blast and thermal effects. The initial thermal pulse, of course, travels at the speed of light and affects materials prior to the arrival of the blast wave. In one series of weapon tests, a two-story white frame house was severely charred by the thermal pulse but fire did not ensue. It was first thought that ignition had taken place and the blast wave had blown out the flames. High speed photography in The Effects of Nuclear Weapons, however, showed that a thick layer of smoke was emitted from the surface of the building, but flames did not occur. The results of the test, therefore, give no information on this problem since it has been found that thick materials can sustain extremely high thermal pulses (much greater than 100 cal/cm^2) without sustaining ignition. Therefore, only the kindling fuels are of interest when considering primary ignitions.

In 1950 a study--Fons, et al. (1950)--was made of the blast and thermal effects of a nominal nuclear weapon on a forest. Table B-1 shows some pertinent data on the timing of the thermal and blast phenomena. The following conclusions were reached.

Table B-I

TIMING OF THERMAL AND BLAST PHENOMENA

Distance from Ground Zero (ft × 10^{-3})	Shock Wave, Positive Phase: Time Arrival (seconds)	Shock Wave, Positive Phase: Duration (seconds)	Shock Wave, Positive Phase: Maximum Wind Velocity (mph)	Radiant Energy Received (%): Before Shock Front	Radiant Energy Received (%): During + Phase	Radiant Energy Received (%): After + Phase
0	0.70	0.33		58	17	30
1	0.91	0.37	800	65	12	23
2	1.3	0.45	550	79	9	12
3	1.9	0.62	380	90	7	3
4	2.6	0.77	270	97	3	
5	3.2	0.90	200	100		
6	4.0	0.98	160	100		
7	4.7	1.1	125	100		
8	5.5	1.1	100	100		
9	6.3	1.2	80	100		
10	7.2	1.2	70	100		
12	9.0	1.2	50	100		
14	10.8	1.3[a]	40[a]	100		
16	12.6	1.3[a]	30[a]	100		

a. Extrapolated.

Source: Fons, et al. (1950).

"From the table it is seen that within the radius of potential ignition, out to 10,000 feet, incipient fires will be hit by the shock front within 0.7 to 7.2 sec after detonation. As ignition is not instantaneous, particularly at the greater distances, the interval between ignition and arrival of the shock front is even less. So incipient fires will not be well established when hit by the cooling winds. And as only fuels directly visible from the fireball will be ignited, many will also face the full force of the positive phase of the shock wind. Many incipient fires will be blown out. In addition, falling branches and debris from trees may tend to beat out some. . . .

"Even though many incipient fires are blown out, it is believed now that enough will persist to be potentially dangerous where conditions are otherwise favorable for burning. Persistent ignitions are probable in punky wood, which is common in all wooded areas, and in loose beds of litter fuels. In the latter, ignition may take place one-half inches or more below the surface where shock winds may not penetrate.

". . . Where the shock force has a strong vertical component near ground zero, it is also possible that the overpressure may actually increase the rate of combustion and thus even more firmly establish ignition."

A series of tests were undertaken by the University of California at Los Angeles in 1951 to study the effect of blast in extinguishing fires. The first phase of the project, V. Tramontini and R. Simonson (1952), resulted in the design and development of an appropriate thermal source and test to determine the energy required to ignite light fuels, such as pine needles, punky wood, grasses, leaves, and litter.

The second phase, V. Tramontini and P. Dahl (1953), resulted in the development of equipment to impose the blast-wind air flow on fuels ignited by the radiant source and to determine the effects of the air flow on burning samples of pine needles, madrone leaves, cheat grass, punk, and crumpled newspaper, under various conditions.

The results of the second phase suggest that ignitions may be extinguished in certain fuels subjected to overpressures of at least 2 to 4 psi, depending on distance from an atomic bomb. However, conditions in the field could not be duplicated in the laboratory, and the effect of restraining the fuel during blasting could result in lower extinction

velocities than would be required in the field. Statistically, the velocities required for 10 percent and 90 percent probability of extinction were about 18 percent below and above the velocity for 50 percent probability of extinction for pine needles. For beds of pine needles, the blast winds required for extinction were about the same for vertical as for horizontal orientation, but for other fuels the results are inconclusive.

Figures B-3 and B-4 show the effects of extinction velocity of air flow time and of fuel burning time. In Figure B-3, two broken lines show the relationship between peak pressure and flow time for weapons of 27 and 500 kt. In Figure B-4, the shaded bands cover ranges in bulk density of 1.5 to 3.2 lb/ft^3, the lower density requiring the higher velocity. In both figures, $\bar{M}$ is the moisture content of the fuel, and the extinction velocity is that velocity which gives 50 percent chance for extinction.

The final phase of the UCLA blast studies, Dahl and Guibert (1954), describes the completion of tests on crumpled newspaper, blue denim fabric, and muslin-sheeting fabric. Specimens were oriented vertically, horizontally, or at a 45° angle to the test apparatus. A thermal pulse ignited the materials, and after a specified time, a blast wave was generated. A threshold velocity was again defined as that velocity for which the probability of extinction of fires in the materials tested was approximately one-half. The variables in the experiments were the following:

V_o^* = maximum duct air velocity for threshold extinction (ft/sec)

θ_F = total time of air flow (sec)

$\bar{\theta}_B$ = average burning time (sec)

$\bar{M}$ = average fuel bed moisture content (percent)

$\bar{D}$ = average fuel bed bulk density (lb/ft^3); for fabrics, the weight per unit area (oz/yd^2).

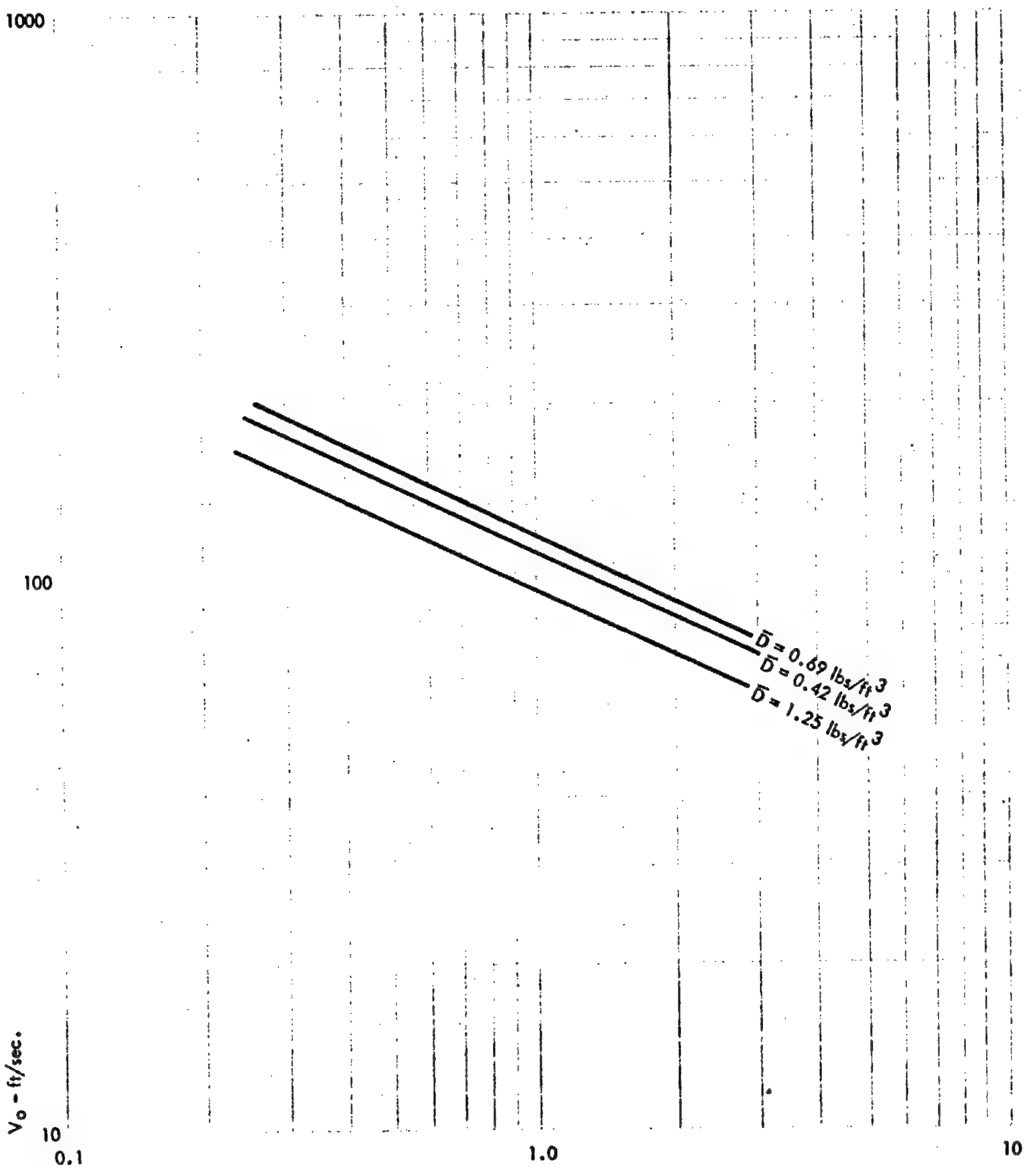
A few examples of the results are shown in Figures B-5, B-6, and B-7. These data have apparently not been correlated with weapon phenomena. Unfortunately, the range of the variables tested does not permit a direct application of the results to thermonuclear devices. For example, the largest $\bar{\theta}_B$ tested, i.e., time for the burning to develop, is 10 seconds. At a height of burst of 500 feet and a distance of one mile from ground zero, the arrival time of the blast wave is about 4.0 seconds

Classified Figure B-3 on extinction velocity vs flow time has been deleted.

Classified Figure B-4 on extinction velocity vs burning time has been deleted.

Figure B-5

THRESHOLD EXTINCTION VELOCITIES AS A FUNCTION OF FLOW TIME



FLOW TIME, θ_F - seconds

NOTE: Fuel - Crumpled Newspaper
Atitude - Horizontal; θ_B = 5.0 sec
$\bar{M}$ = 8.9%

SOURCE: Dahl and Guibert (1954)

Figure B-6

FIRE EXTINCTION PROBABILITY VS MAXIMUM WIND VELOCITY

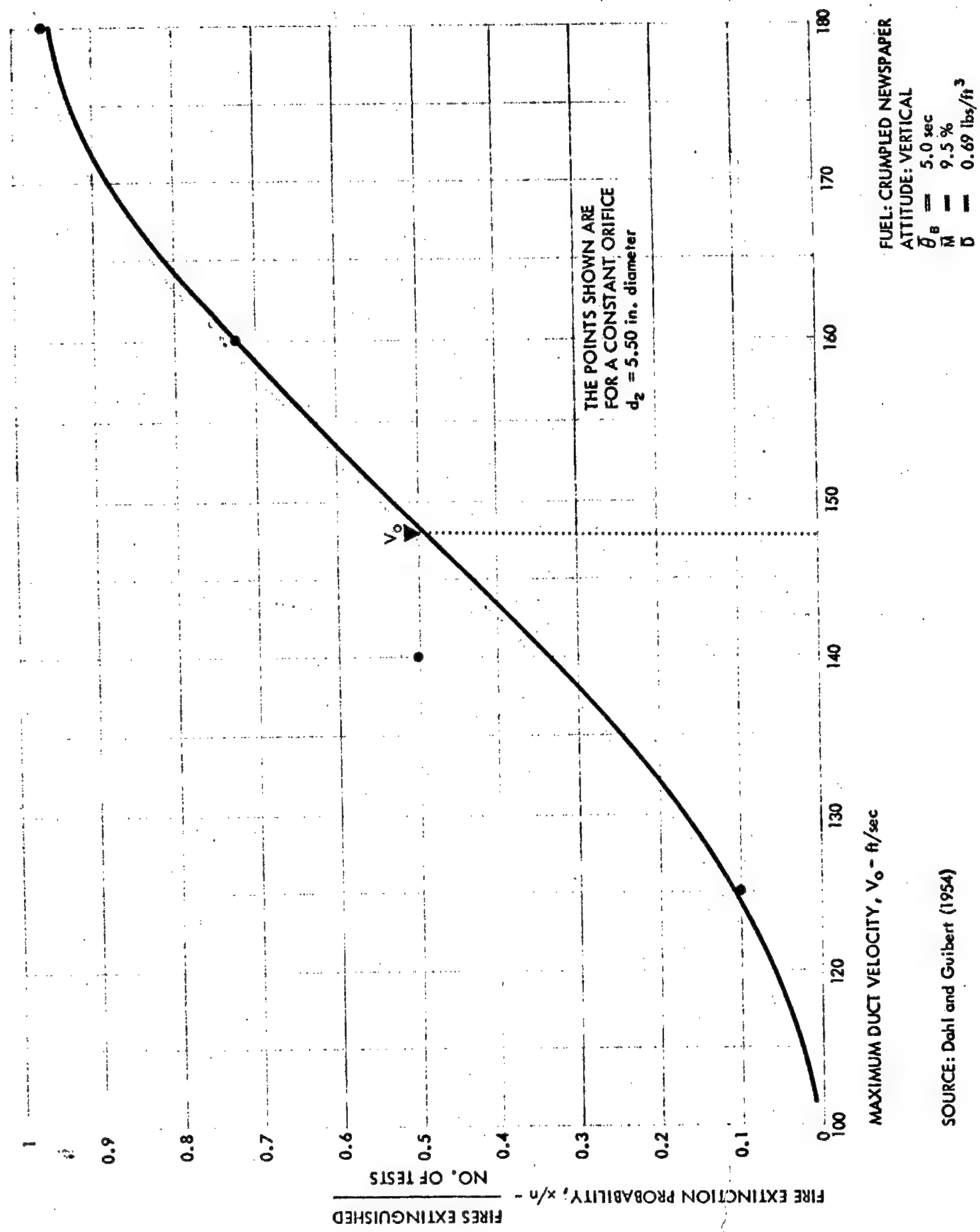
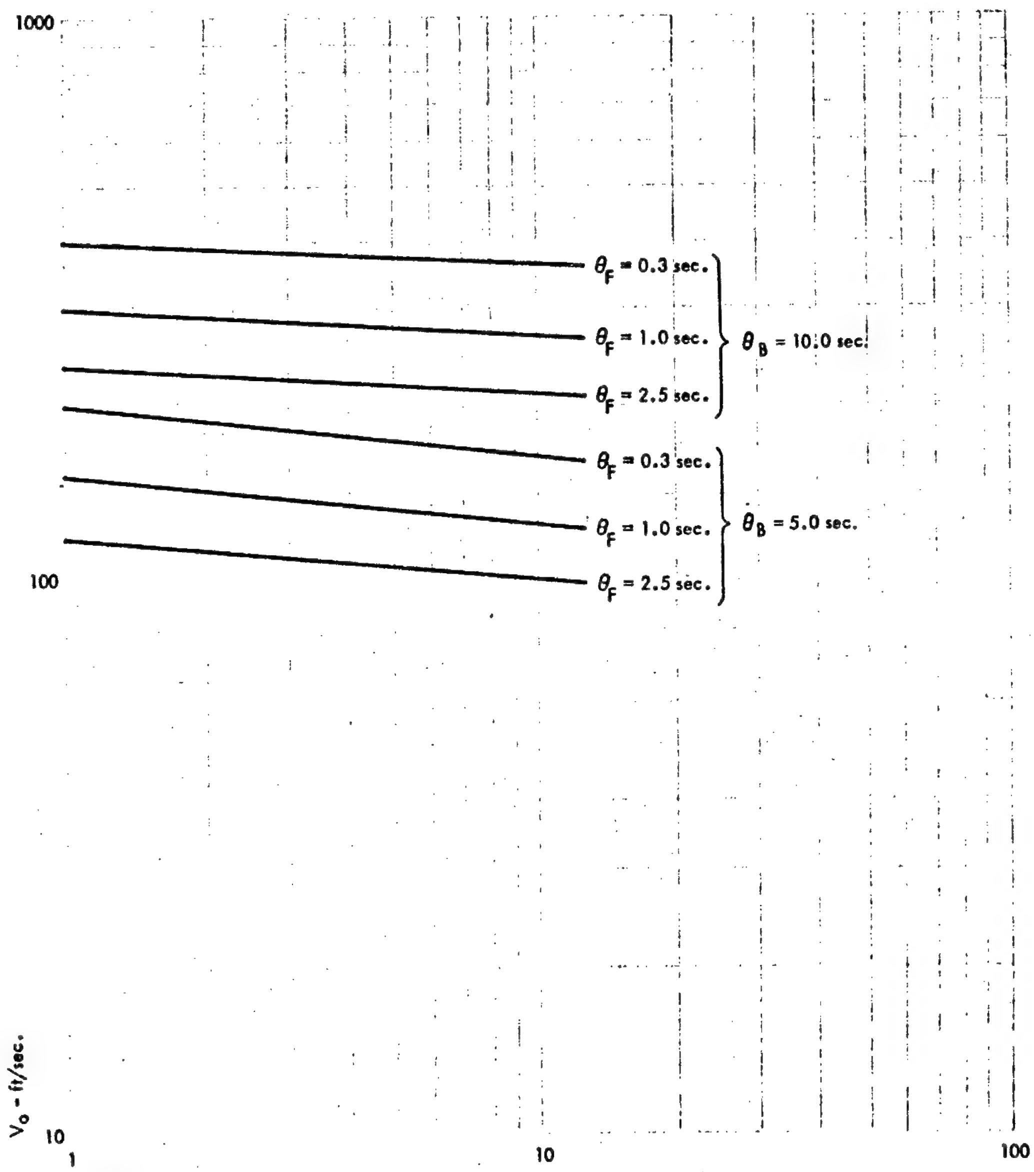


Figure B-7

EXTINCTION VELOCITY VS MOISTURE CONTENT



MOISTURE, $\bar{M}$ - percent

NOTE: Fuel - Blue Denim Fabric
Attitude - 45°
$\bar{D}$ = 8.8 oz Pleated

SOURCE: Dahl and Guibert (1954)

for 1 kt. The corresponding arrival time for 1 mt is about 40 seconds. This means that the burning process is more firmly established with the larger yield.

In their extensive survey of fire literature, Salzberg, et al. (1960) have found two other references concerning the behavior of fires that are subject to blast waves.* The following summaries are abstracted from Salzberg, et al. (1960).

> "Streets [1953] indicates that blast winds extinguish some fires in grass and in fine fuels when peak particle velocity is greater than 120 ft/sec (associated with 2.2 psi) and in thicker fuels when it is greater than 170 ft/sec (associated with 3.0 psi). . .
>
> "Prepared fuel beds of conifer needles, hardwood leaves, grasses, and rotten wood are exposed in Operation Snapper to total energies varying from 1-22 cal/cm^2 [Arnold, 1952]. Thickness and density of fuel particles are determined prior to the test. Fuel moisture at shot time is measured in duplicate fuel beds, similarly located but outside the test area. Post-test fuel examinations show that punky materials and fine grasses ignited and continued to burn at distances from ground zero where total thermal energy was approximately 3 cal/cm^2. Following Shots 3 and 4, punky materials were still burning upon recovery at H + 2 hours."

Unfortunately, the Operation Snapper tests were all made with low yield weapons--the highest yield was 31 kt; all others were less than 20 kt.

D. L. Martin (1957) has investigated the possible use of blast from atomic weapons intentionally detonated to extinguish mass fires. He concludes that "expansion rather than extinguishment may be expected when an explosive is detonated immediately over a firestorm."

As a final point, blast from nuclear weapons is important to the evaluation of fire potential in that buildings destroyed by blast would create barriers, seriously handicapping the work of firemen and rescue workers. This problem has never been studied, but case histories from World War II indicate that even half-tracked vehicles were stalled by the rubble; see Bond (1955).

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* These references were not available to the author at the time of this writing.

Interactions between Radioactive Fallout and the Threat of Fires

An apparently important phenomenon which has been ignored by all investigators except Broido and McMasters (1959) is the effect of mass fires on fallout distribution. At a medical colloquium, Dr. Broido (1962) made the following remarks.

> "Mass fires produce convection columns with updrafts strong enough to move rather sizeable objects. Fallout patterns have been observed in experiments in the Nevada desert and over the Pacific Ocean where, since neither sand nor water can burn too well, few fires have been formed. I strongly suspect, and our wind tunnel experiments tend to confirm this suspicion, that in a region where mass fires are produced, the fallout distribution will be totally unlike that predicted from observations in Nevada or in the Pacific. Our wind tunnel experiments indicate the patterns will be moved further downwind; fallout will spread over a much larger area, with a considerable reduction in the highest levels found."

The experiments referred to were conducted in a 6 by 6 foot low-velocity wind tunnel, using full-scale fallout simulants. The results suggest quite strongly that effects which can markedly influence civil defense planning will be found for large-scale fires. Since the effect on fallout distribution can be significantly influenced by air flow into and around the column, open air experiments on a larger scale are recommended in Broido and McMasters (1959) so that such flow will not be affected by the tunnel walls and ceiling.

Another effect which must be considered is the danger from fallout to the fire-fighting personnel. Frank McNea (1961) has illustrated this by a hypothetical case which established a 10-mt surface burst, a 10-mph wind, and a 10-r/hr contour as a safety level criterion. Under these conditions, he estimates that during the first day, fire-fighting personnel could perform emergency operations to within six miles of ground zero on the upwind side. During the second day, they probably could enter the area to within four miles of ground zero on the crosswind side. Very little emergency operations or recovery measures could be undertaken downwind of ground zero before one or two weeks although radiological monitoring might indicate discontinuities in the fallout field which could be exploited in rescue operations.

Interactions of the Thermal Pulse with the Physical Environment and the Target System

The characteristics of the thermal pulse shape have already been considered, as well as the variation of these characteristics with yield, altitude, and range from the target. Additional modifications may occur before the energy reaches the target. However, the pulse may be significantly modified by the physical phenomena of weather, atmospheric transmissivity, and topography. These modifications will be discussed first; followed by the effects of the resultant thermal pulse on the target complex and the relation of the ignitions caused by the thermal pulse to the development and spread of fires.

In this section, primary emphasis will be on the transmission of the thermal energy from the burst to the target area and its modification by clouds, visibility factors, surface reflectivity, and other meteorological variables. In addition, mention will be made of the effects of topography on the thermal radiation.

Modification of the Thermal Pulse by Physical Environment

The purpose of meteorological research on fire processes is to provide estimates of initial thermal radiation at ground level which can be used in conjunction with estimates of target material characteristics and distribution to determine the size and shape of the initial ignition areas. The meteorological problem resolves naturally into two divisions. The first is the mathematical and physical determination of the amount of thermal energy transmitted through the atmosphere from the burst to the target area under all pertinent meteorological conditions and burst geometries. The second, which will be considered in a later section, is the determination of the distribution of these conditions in the various potential target areas and on a national scale. These combined estimates can then be used as the initial conditions in the determination of the fire spread and damage estimates which are, of course, the ultimate purpose of the research.

The transmission factor, T, has been defined earlier as the ratio of incident radiation in the presence of the atmosphere and the earth's surface to the energy received in the absence of such environment. This factor modifies the thermal energy according to equation (5),

$$Q = \frac{ET}{4\pi R^2} \qquad (5)$$

where Q is in cal/cm^2, slant range R is in centimeters, and E is the total thermal energy emitted, in calories. Substituting $E = 10^{12}$ fW, where f is the fraction of the yield which appears as thermal energy and W is the yield of the burst in kilotons, and putting $R^2 = d^2 + h^2$, where d is the distance from ground zero and h is the burst height, the equation becomes

$$Q = \frac{1.04\ WT}{d^2 + h^2}$$

where Q is again in cal/cm^2, d and h are in miles, and f has been chosen as 1/3; see Glasstone (1962).

Figures B-8 and B-9 present plots of this equation for various warhead yields to indicate the relative importance of the different variables over the ranges of interest. Note, for example, that a change in the transmission factor from 1.0 to 0.1 will decrease the radiation from a 10-mt burst to approximately that of a 1 mt with a 1.0 transmission factor. (The burst altitudes in these two figures are those which will give maximum radii for 4-psi overpressure.)

In Figure B-9 the distance from ground zero, or ignition radius in this case, is based on typical ignition requirements from Miller (1962). In Miller, the ignition requirements for a given material vary with yield according to the following formulas:

$$Q = Q_f W^{0.1}, \text{ for } 1 \leqslant W \leqslant 5.2 \times 10^3$$

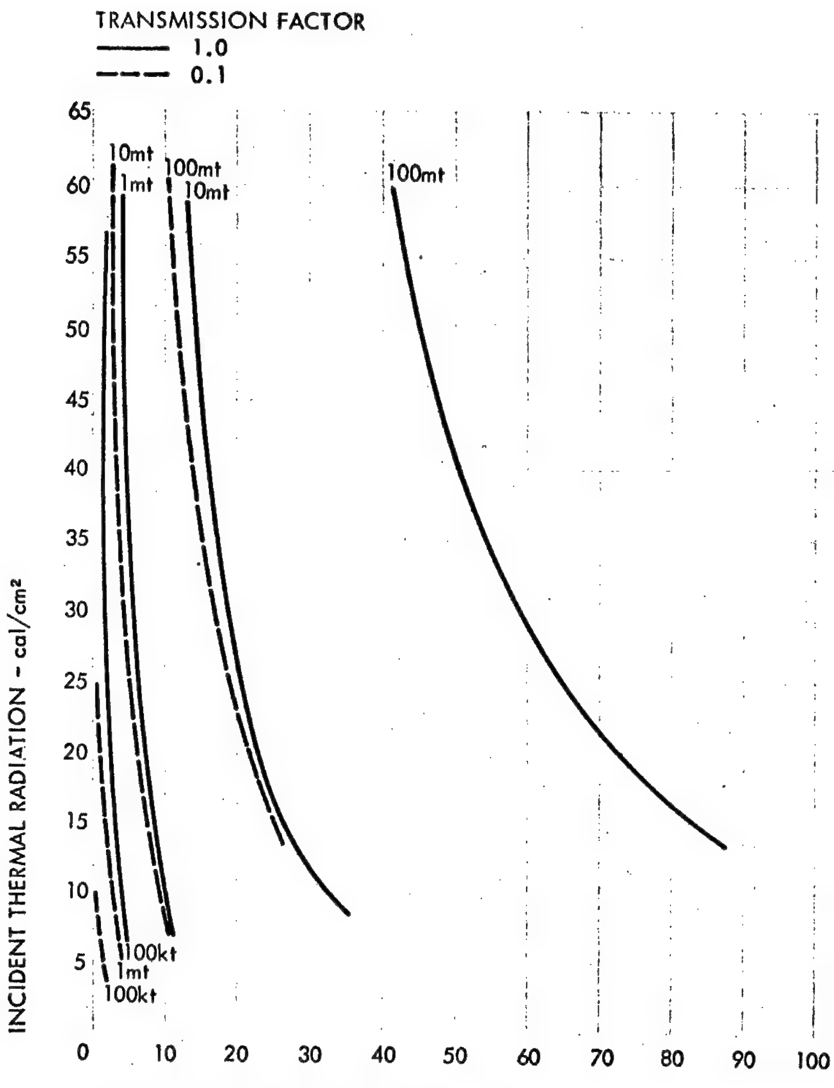
and (21)

$$Q = 0.425 Q_f W^{0.2}, \text{ for } W > 5.2 \times 10^3$$

where Q_f is the ignition requirement (in cal/cm^2) for a 1-kt burst, and Q is the ignition requirement (in cal/cm^2) for a burst of W kilotons. As discussed elsewhere, the total thermal energy required to ignite a given material increases with yield since the rate of delivery of the energy decreases with yield. The value of Q_f used here (6 cal/cm^2) was derived by Miller (1962) from the values given in Glasstone (1962). This value is representative of the materials most likely to be involved as primary causes of fire initiation, such as curtains, upholstery, paper cartons, pine needles, and the like. As discussed later in this appendix, there are wide variations in the estimates of ignition requirements

Figure B-8

THERMAL RADIATION VS DISTANCE FOR VARIOUS YIELDS AND TRANSMISSION FACTORS (receiver normal to radius vector)

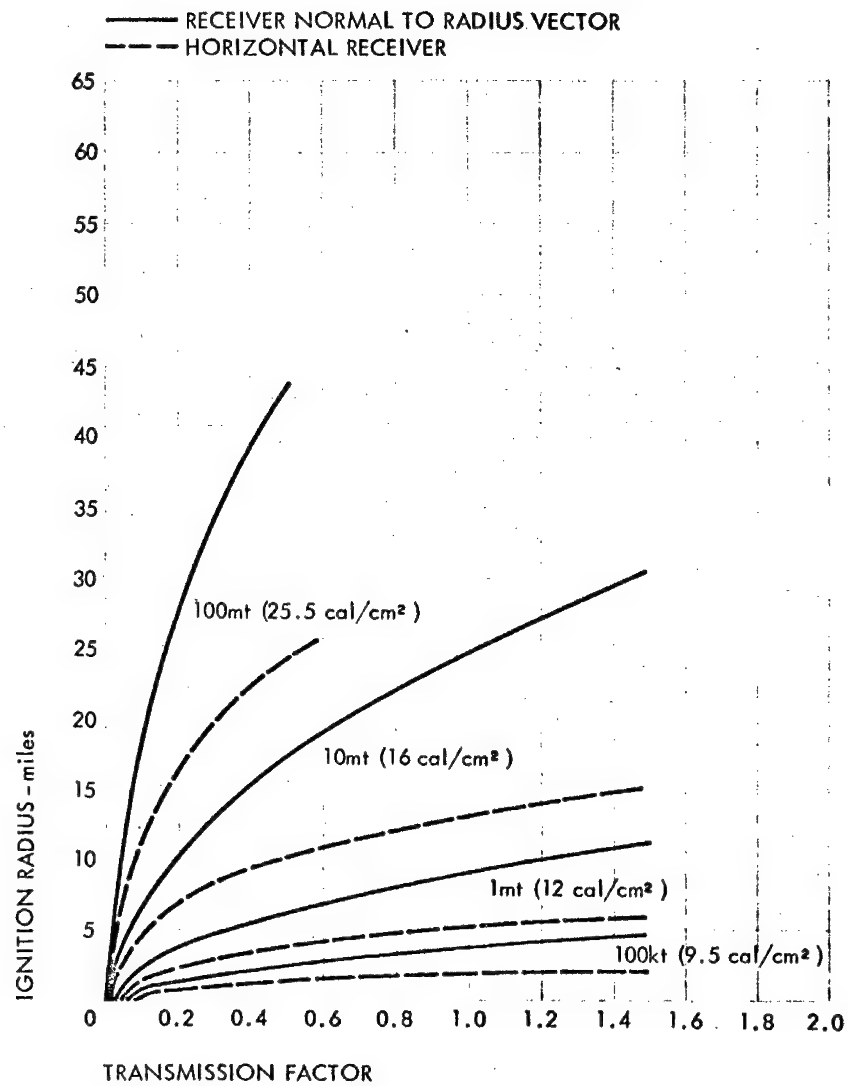


NOTE: Burst height optimum for 4 psi

SOURCE: Based on Glasstone (1962)

Figure B-9

IGNITION RADIUS VS TRANSMISSION FACTOR



NOTE: Optimum burst height for 4 psi

SOURCE: Miller (1962), Glasstone (1962) and Stanford Research Institute

(see Table B-VII). The ignition radii given in this section can therefore be considered upper limits; if it is desired to identify ignition radii with particular materials, kraft paper cartons or pine needles are appropriate to use. Note from Figure B-8, however, that small variations in thermal radiation requirements have little effect on ignition radius, particularly at distances corresponding to typical city sizes. Since the transmission factor, T, varies with distance from the burst and, in most cases, decreases with increasing distance, these curves give only a partial indication of its effect.

The determination of T under all pertinent conditions of visibility, cloud configuration, particulate content, ground cover, and burst geometry is an exceedingly complex problem. Furthermore, a different value of T must be used for a target complex than for an element of the complex since orientation, shielding, and reflections within the target area significantly modify the ultimate energy falling on a window curtain, a building, an inhabitant, and the like. The effects within a target area will be considered later. Here, only the value of T for the entire complex will be discussed.

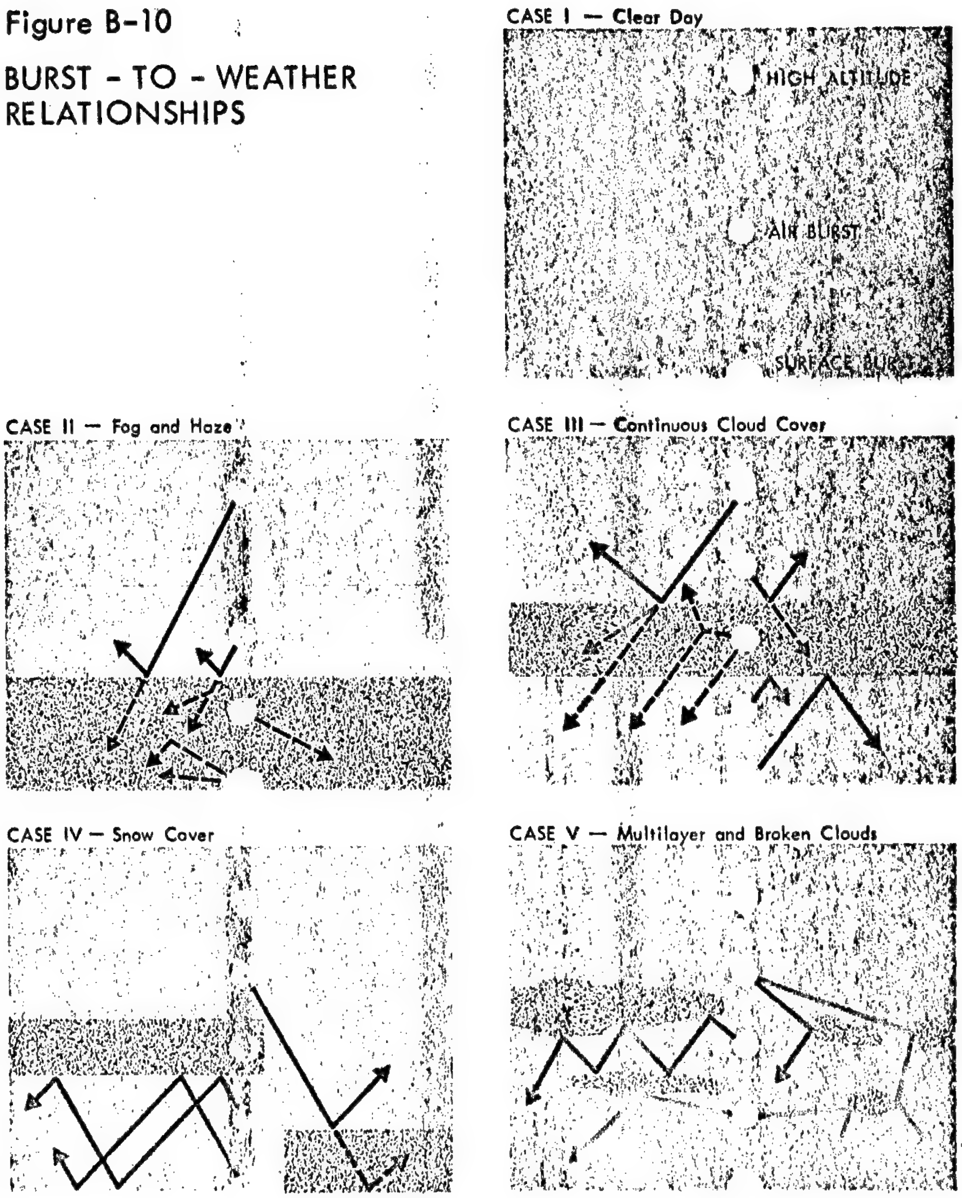
While the transmission factor has received some attention in the literature, it was not until recently that adequate numerical results were obtained for even a representative range of variables. Because of the complexity of the problem, all the results to date have included a variety of approximations, partly for computational reasons and partly because of a lack of physical data.

Figure B-10 presents some rather elementary sketches of five types of important situations. For each of these cases, the computational problem and detailed physical description are given. This section is primarily concerned with the air burst since the high altitude or above the atmosphere burst is covered by Passell (1963) and the surface burst has in general a smaller radius of thermal effect than an air burst.

Case I (Clear Day) and Case II (Fog or Haze). On a perfectly clear day, with little or no water vapor in the atmosphere, the primary attenuation is caused by Rayleigh scattering (elastic scattering by the air molecules themselves), by absorption by carbon dioxide, and in the case of higher altitude bursts absorption by ozone. The surface of the earth also plays a role by reflecting the radiation back into the atmosphere; part of this radiation is in turn scattered back to the earth's surface. The albedo, or fraction of the incident radiation which is (diffusely) reflected, can vary from as little as 2 or 3 percent for black earth and coniferous forests to as much as 86 percent for snow (Case IV); see Handbook of Geophysics.

Figure B-10

BURST - TO - WEATHER RELATIONSHIPS



SOURCE: Stanford Research Institute

As the water and particulate content increases and visibility, or more exactly, the meteorological range,* decreases from that on a perfectly clear day (approximately 160 miles) to what might be called an ordinary clear day, the scattering and absorption by the larger particles play an increasing role. The actual decrease in thermal radiation received is much less than the decrease in visibility. The visibility is in effect a measure of the difference between the direct component and the scattered component of radiation while the radiation actually received is the sum of these two components. For example, a decrease in visibility from 50 miles to 10 miles in the case of a 10-mt burst at 5,000-foot altitude causes a change in the distance from ground zero at which 16 cal/cm^2 is received from about 14 miles to about 8.5 miles. (Note: the value of 16 cal/cm^2 is derived from equation (21) above and is representative of the total energy required to ignite kraft paper cartons or dry pine needles for the pulse shape estimated for a 10-mt burst. This same value is used extensively in the figures in this appendix and, as mentioned above, provides an upper limit for the ignition radius of a given material because of the uncertainty in ignition requirements. Since the thermal radiation at a given point is directly proportional to yield, the curves can be used directly for other ignition requirements by multiplying the 10-mt yield by the corresponding factor. For example, if the ignition requirement is 32 cal/cm^2 the curves give ignition radii for a 20-mt burst.)

As the particles or droplets increase in size (to about 5 microns)--usually because of increasing humidity--they show selective scattering, often appear bluish in color, and are called haze; see Malone (1951). As the particle size increases further, the selective scattering is almost gone and fog results, which is ordinarily colorless. As can be seen in the figures below, there is no strict one-to-one correspondence between the visibility and the ignition range since the water vapor, droplets, and particulate content of the atmosphere affect each of these parameters in a somewhat different manner. In addition to distribution of particle and water droplet by size and altitude, an exact analysis of the transmission factor for Cases I and II requires the incorporation of at least the following data:

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* The meteorological range is the distance at which a (large) dark object has a brightness (luminance) contrast against a horizon background of .02. In practice, the visibility as determined by weather station observation can differ appreciably from the meteorological range because of local conditions and the availability of appropriate landmarks.

1. Air density vs altitude.

2. Water vapor, carbon dioxide, and ozone concentration vs altitude.

3. Scattering coefficient vs angle, wavelength, index of refraction, and particle type and size.

4. Absorption coefficient vs wavelength and particle type.

5. Surface (and fog top) reflectance vs wavelength.

6. Weapon thermal radiation spectrum vs time.

7. Burst-target geometry.

Many of these individual aspects of the problem have been thoroughly studied; others have been investigated to a much lesser extent (see bibliography of Passell).

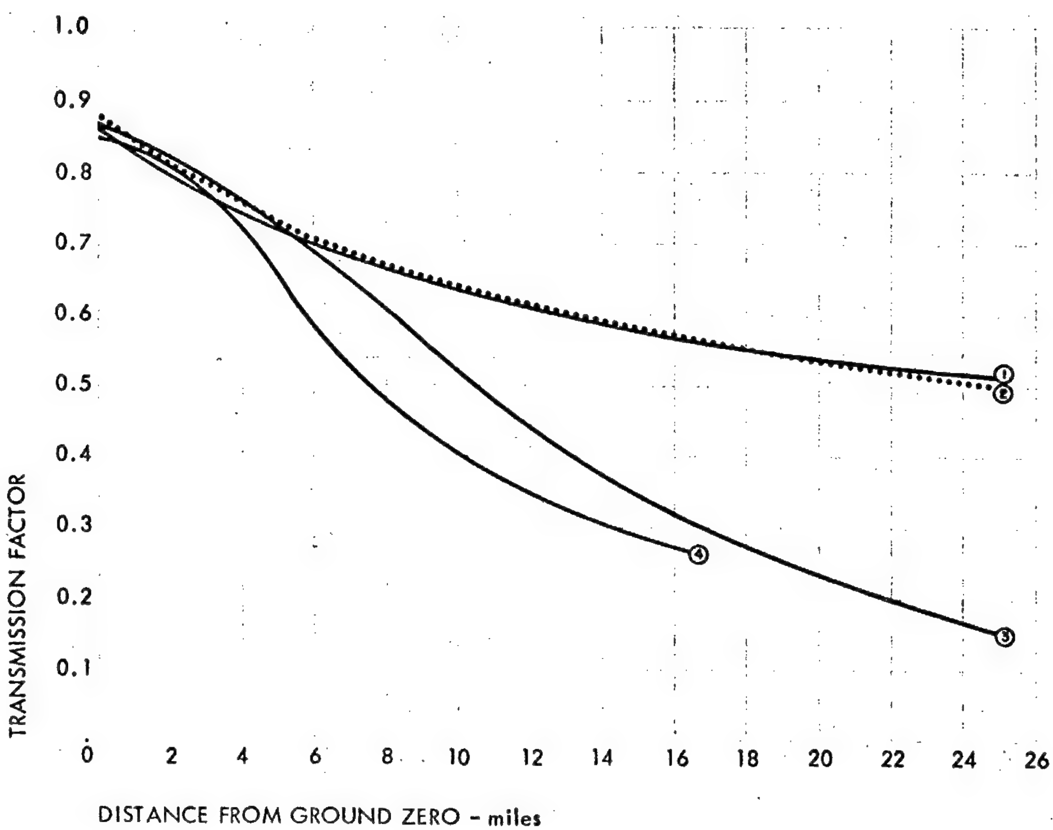
The over-all problem of transmission factor for Cases I and II has been treated at various levels of detail in the literature. Figures B-11 through B-13 present comparisons of some of the results in terms of the transmission factor vs range for various values of visibility and indicate the references from which the results were derived. While exact comparisons are not possible, the conditions shown in Figures B-11 through B-13 were chosen to minimize the effects of the varying assumptions in the different methods. Figures B-14 and B-15 give similar comparisons for ignition radius vs visibility. These numerical examples are contingent to some extent, as are those elsewhere concerning clouds and fog, on the direct effects of thermal radiation on clouds and fog. Whether or not the early radiation will vaporize enough of the cloud or fog to enable the following radiation to be transmitted to a much greater degree has not been investigated in detail.

The upper three curves of Figure B-11 are based on simple empirical relationships designed to apply to values of range equal to or less than about one-half the visibility. Curve 1 is based on variations of diffuse transmittance recommended in Stewart and Curcio (1952). The entire equation, described in Jewell and Willoughby (1960) using the constants recommended in Streets and Marron (1954), is

$$T = (0.6 + 0.4e^{-D/v})(0.52 + 0.48\ t_2)$$

Figure B-11

ATMOSPHERIC TRANSMISSION VS RANGE FOR A VISIBILITY OF 50 MILES—COMPARISON OF COMPUTATIONAL TECHNIQUES
(receiver normal to radius vector)



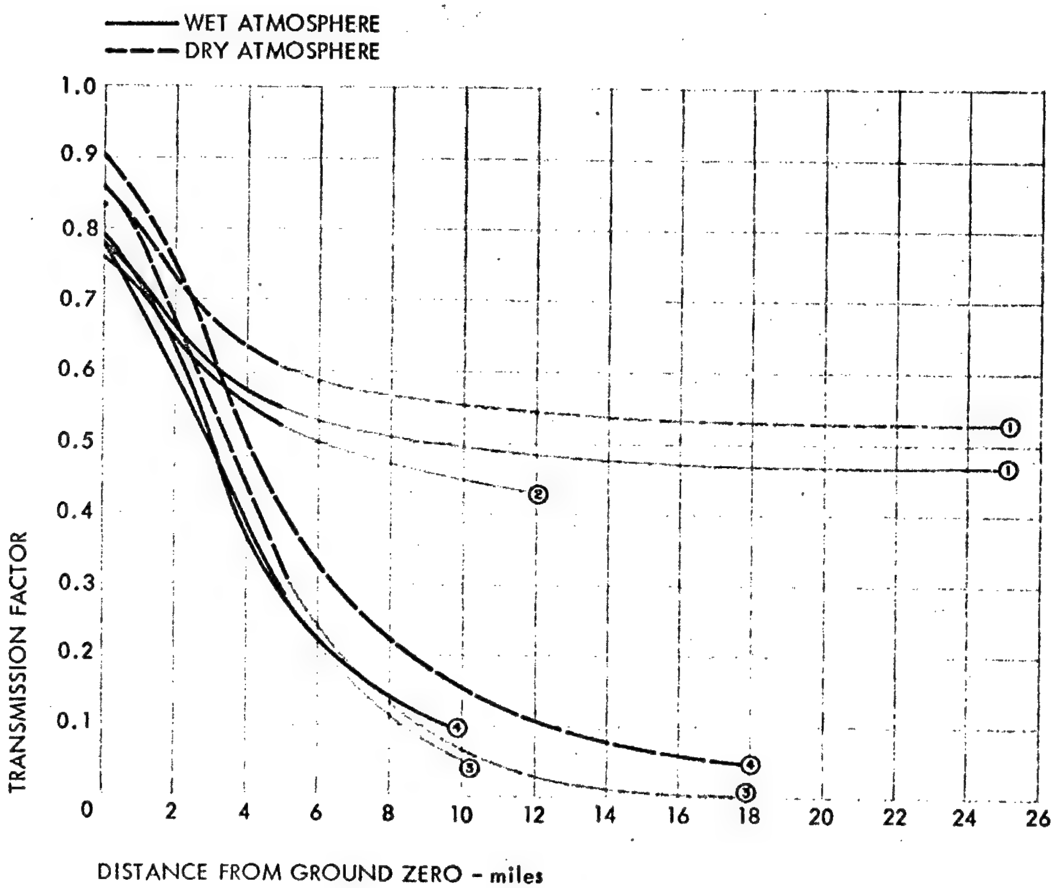
NOTE:Derived by Stanford Research Institute from;

1 Stewart and Curcio (1952), Streets and Marron (1954), Jewell and Willoughby (1960)
2 Glasstone (1962)
3 Gibbons (1958 and 1959), Streets and Marron (1954), Jewell and Willoughby (1960)
4 Cahill, Gauvin, and Johnson (1962)

Visibility = 50 miles
Burst height = 5,000 feet
Wet Atmosphere

Figure B-12

ATMOSPHERIC TRANSMISSION VS RANGE FOR A VISIBILITY OF 10 MILES— COMPARISON OF COMPUTATIONAL TECHNIQUES
(receiver normal to radius vector)

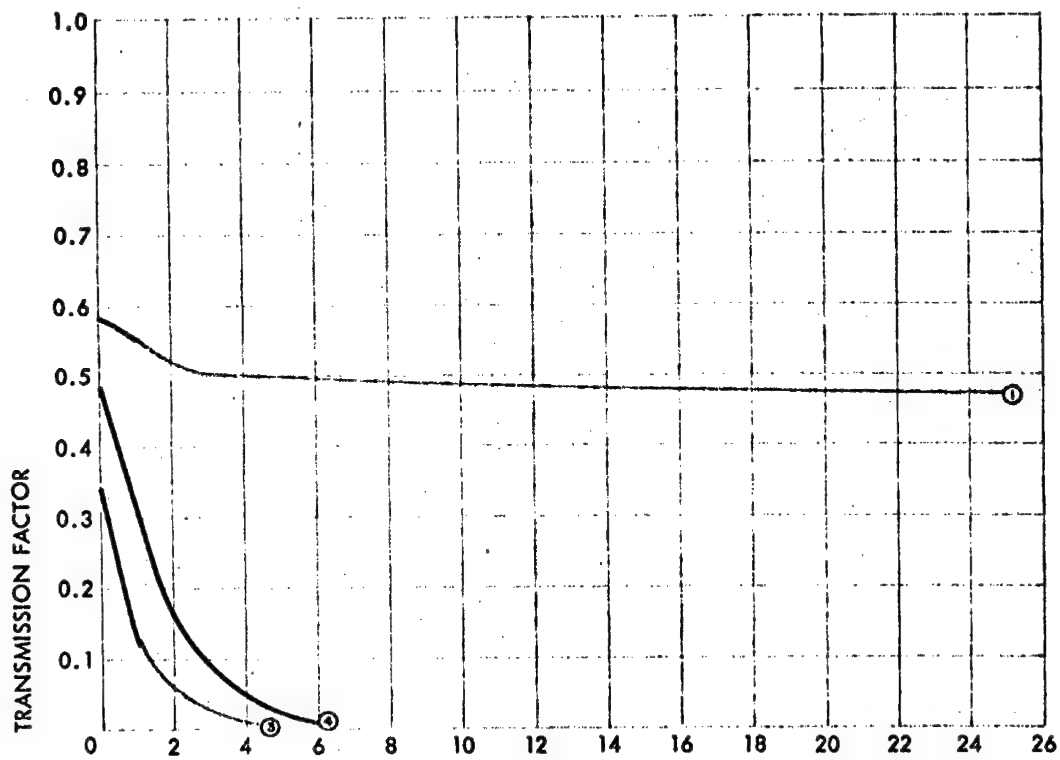


NOTE: Derived by Stanford Research Institute from;
1 Stewart and Curcio (1952), Streets and Marron (1954), Jewell and Willoughby (1960)
2 Glasstone (1962)
3 Gibbons (1958 and 1959), Streets and Marron (1954), Jewell and Willoughby (1960)
4 Cahill, Gauvin, and Johnson (1962)

Visibility = 10 miles
Burst height = 5,000 feet

Figure B-13

ATMOSPHERIC TRANSMISSION VS RANGE FOR A VISIBILITY OF 2 MILES— COMPARISON OF COMPUTATIONAL TECHNIQUES
(receiver normal to radius vector)



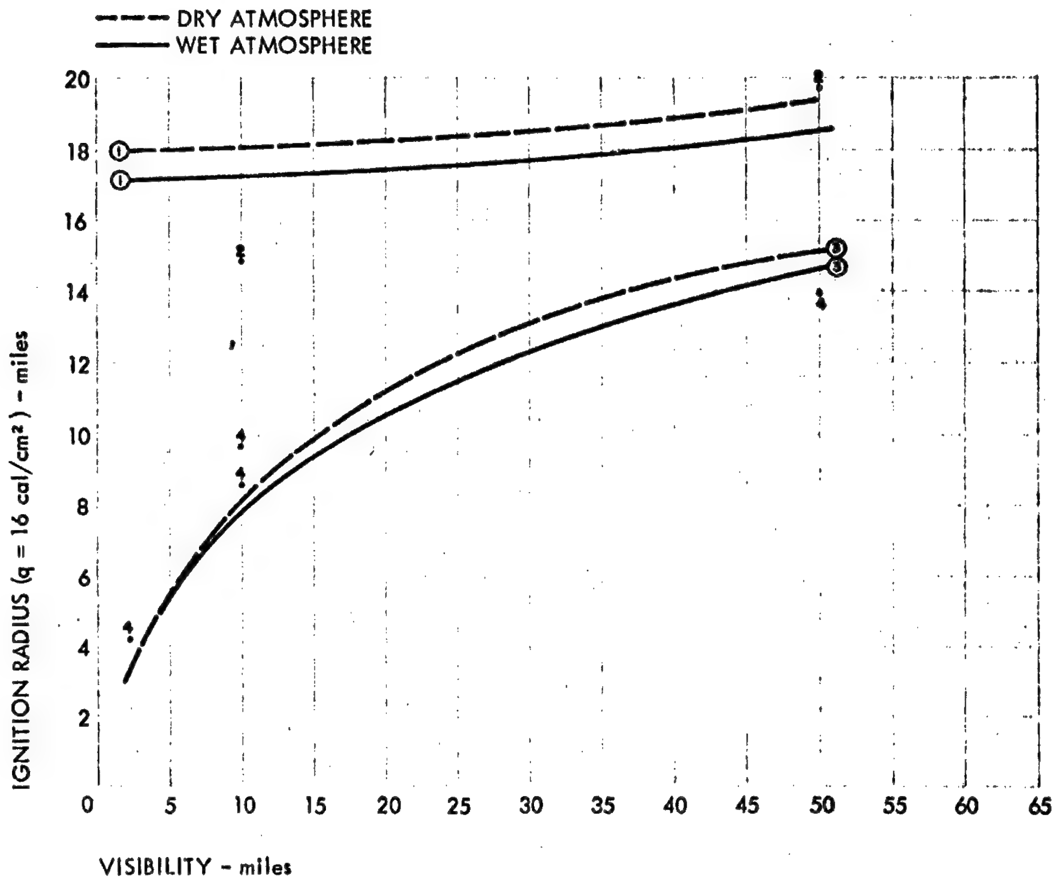
DISTANCE FROM GROUND ZERO – miles

NOTE: Derived by Stanford Research Institute from;
1 Stewart and Curcio (1952), Streets and Marron (1954), Jewell and Willoughby (1960)
3 Gibbons (1958 and 1959), Streets and Marron (1954), Jewell and Willoughby (1960)
4 Cahill, Gauvin, and Johnson (1962)

Visibility = 2 miles
Burst height = 5,000 feet
Wet atmosphere

Figure B-14

IGNITION RADIUS VS VISIBILITY FOR A 10 MT BURST—
COMPARISON OF COMPUTATIONAL TECHNIQUES
(receiver normal to radius vector)

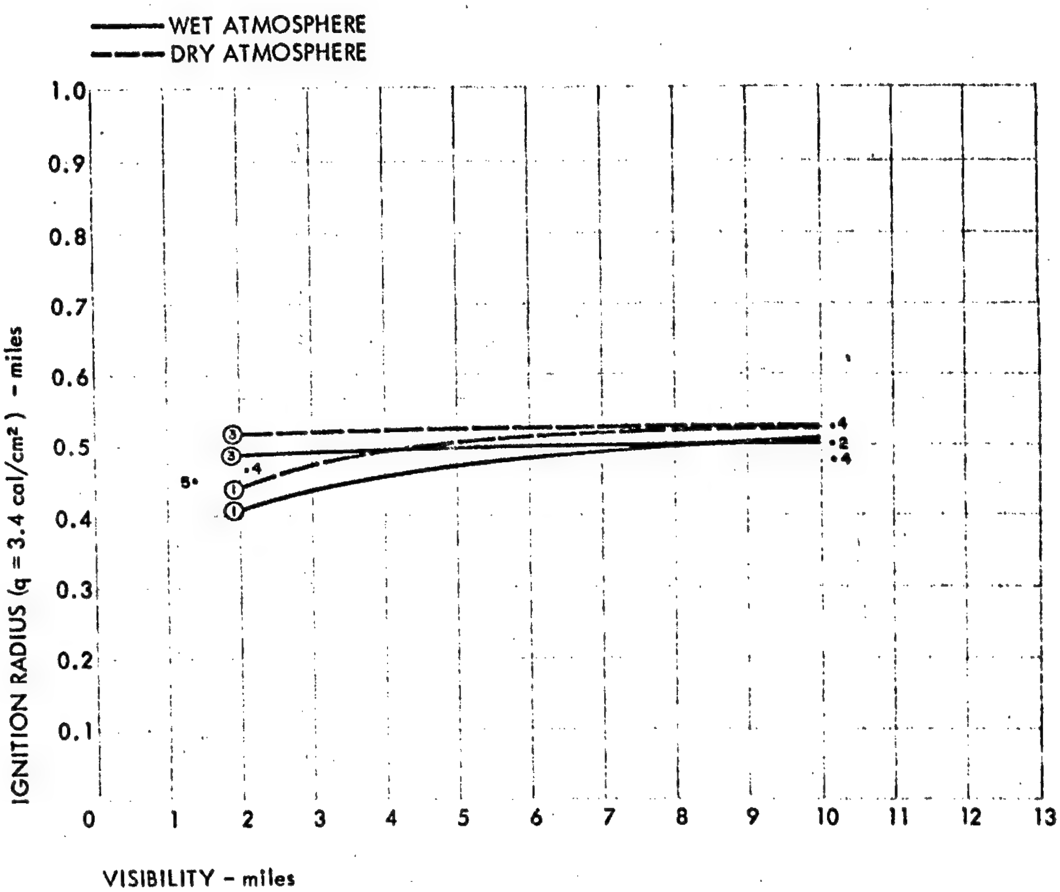


NOTE: Derived by Stanford Research Institute from;
1 Sfewart and Curcio (1952), Streets and Marron (1954), Jewell and Willoughby (1960)
2 Glasstone (1962)
3 Gibbons (1958 and 1959), Streets and Marron (1954), Jewell and Willoughby (1960)
4 Cahill, Gauvin, and Johnson (1962)

Burst height = 5,000 feet

Figure B-15

IGNITION RADIUS VS VISIBILITY FOR A 1 KT BURST—
COMPARISON OF COMPUTATIONAL TECHNIQUES
(receiver normal to radius vector)



NOTE: Derived by Stanford Research Institute from;
1 Stewart and Curcio (1952), Streets and Marron (1954), Jewell and Willoughby (1960)
2 Glasstone (1962)
3 Gibbons (1958 and 1959), Streets and Marron (1954), Jewell and Willoughby (1960)
4 Cahill, Gauvin, and Johnson (1962)
5 Chin and Churchill (1960)

Burst Height = 500 feet

where T is the transmission factor,

$D = (d^2 + h^2)^{1/2}$ = slant range

d = distance from ground zero (miles)

h = height of burst (miles)

v = visibility (miles) and

t_2 = transmissivity of infrared region (wavelength $> 7\mu$)

Similarly, curve 3 is based on later measurements of the diffuse transmittance in Gibbons (1958 and 1959) and involves Jewell and Willoughby and Streets and Marron in the same way. Its equation is

$$T = T_{\mathscr{D}}(0.52 + 0.48\ t_2)$$

where the diffuse transmittance, $T_{\mathscr{D}}$, is obtained from

$$T_{\mathscr{D}} = e^{-3.91\ D/v}(1 + 2.9\ D/v) \quad \text{For } D \leqslant 7 \text{ miles}$$

$$T_{\mathscr{D}} = e^{-3.91\ D/v}(1 + 20.3/v) \quad \text{For } D \geqslant 7 \text{ miles}$$

with D, v, and t_2 defined as above.

The relation between t_2 and w, the water content of the atmosphere between the burst and the point of interest on the ground, was obtained from Streets and Marron (1954). For comparison purposes, w was based on the "wet" and "dry" atmospheres assumed in Cahill, et al. (1962). There the variation of water vapor density, in gm/m^3, was plotted as a function of altitude, z, in kilometers, for the two atmospheres which had, respectively, totals of 14 cm and 0.5 cm of precipitable water.*
The following equation was used to find w:

$$w = \frac{(h^2 + d^2)^{1/2}}{h} \int_0^{h'} \rho(z)\ dz$$

* Precipitable water is the water content of the atmosphere.

where w is the precipitable water in millimeters and h' is the burst height in kilometers.

Cahill, et al. (1962) and Chin and Churchill (1960) have presented results of detailed numerical integration of most of the factors in the problem, the former giving a fairly wide range of parameter values as shown in Table B-II and the latter giving a single numerical example, which dictated the use of such a low yield in Figure B-15.

Table B-II

MODEL ATMOSPHERES USED IN CAHILL, GAUVIN, AND JOHNSON

I. Tropic--ocean or land surface

Wet atmosphere (14 cm precipitable water)

0.20 surface albedo
10-mile and 50-mile visual ranges

II. Temperate--ocean or land surface

Wet atmosphere (14 cm precipitable water)

0 surface albedo
2-mile visual range

Dry atmosphere (0.5 cm precipitable water)

0.20 surface albedo
10-mile visual range

III. Arctic--snow field, desert, or solid cloud undercast

Dry atmosphere (0.5 cm precipitable water)

1.00 surface albedo
10-mile and 50-mile visual range

Note: Transmission factors are computed for burst heights of 0, 5,000, and 30,000 ft for all atmospheres.

Source: Cahill, et al. (1962).

A major problem in the solution of the radiation transport problem in a scattering and absorbing atmosphere has been the handling of the distribution of particle size. Since the scattering coefficient of a suspended particle is a strong function of its size, this distribution can be important. Cahill, et al. (1962) and Chin and Churchill (1960) handle this problem in different ways.

The former uses a semiempirical technique to establish a gross scattering coefficient expressed as a function of distance and altitude.* It also uses a similar technique to take into account the fact that the atmosphere is both a scattering and an absorbing medium.

Chin and Churchill (1960), on the other hand, uses a direct integration of the particle-size distribution, as well as a fairly exact approach to the scattering-absorbing problem.**

The degree to which these two techniques differ and whether the degree of uncertainty in physical input data will mask any differences between them are questions worth investigating. In any event, the results of Cahill, et al. (1962) will be used here for illustrative purposes since they cover a range of values, and, in addition, the method has been programmed for machine computation. Note, however, from Figures B-11 through B-13 that the curves numbered 3 are sufficiently close to what appears to be the more exact methods to justify their use where a much simpler approximation is desired. In fact, further comparison at the other conditions which have been investigated would be well worthwhile for discovering the range of validity of this approximation.

<u>Case III (Continuous Cloud Cover)</u>. Probably at least as important as the case of a clear day is that of continuous cloud cover. Here, three burst positions are of interest--above, within, and below the cloud. For the case of the burst above the cloud, there are sufficient data, both theoretical and empirical, on cloud "transmission" to

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* The tranmission factors in Cahill, et al. are given for a hemisphere (flat) receiver pointed in the direction of maximum intensity of incoming radiation, an "optimally oriented receiver," and not necessarily directly at the burst as is the situation in most of the other references. For the purposes of this report, this should make little or no difference.

** See Passell (1963) for a more detailed description of the two methods.

make some simple estimates of initial ignition radii.[1] For a burst in or below the cloud, the situation is more complicated,at least for initial estimates. Here the reflected radiation from the surface of the earth and from the bottom of the cloud both must be taken into account. For a burst within the cloud, the absorption and scattering upward by the cloud must also be accounted for. Hence, the results may be very sensitive to the exact relationship of the burst location to the cloud; see Duckworth, et al. (1953). If the burst is just below the cloud, much of the radiation will be reflected (actually scattered) downward by the cloud. If the burst is in the middle of the cloud, half of the scattered radiation will be directed downward and half upward. If the burst is just above the cloud, much of the radiation will be reflected upward by the cloud.

Figure B-16 presents estimates of ignition radius for a burst above the clouds. Ignition radius is plotted as a function of cloud transmission, the fraction of energy which is transmitted through the cloud. Also indicated are typical transmission values for various cloud types, based on the ratio of insolation with overcast sky to insolation with cloudless sky given by Haurwitz (1948). Different values of burst altitude are given to indicate its effect and to account for the variation in altitude with cloud type. The dotted transmission ranges indicate the higher altitude clouds. The ignition radii here are shown for a horizontal (hemispherical) receiver for two reasons: (1) the values of insolation are generally measured on the horizontal and (2) the below-the-cloud case discussed later has been computed for a horizontal receiver only. Also, the computations are based on a nonscattering, nonabsorbing atmosphere (except, of course, for the clouds), allowing the use of the simple equation

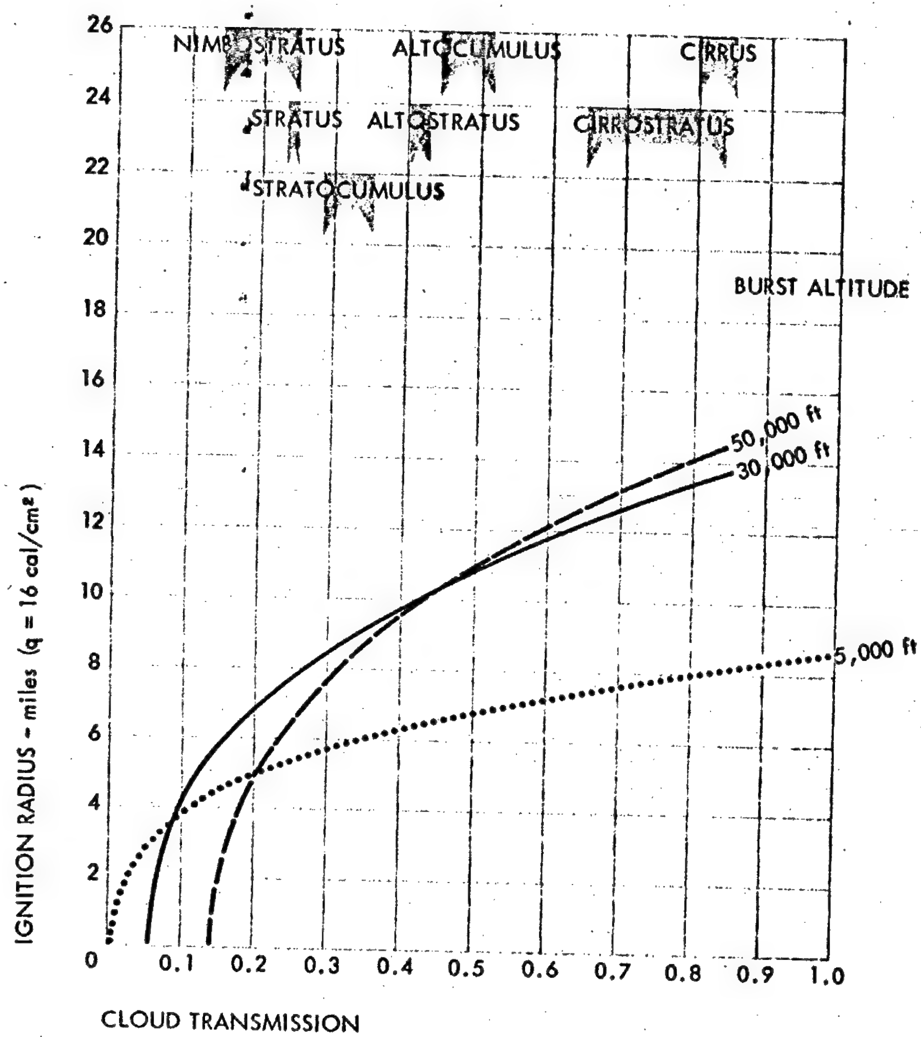
$$Q = \frac{1.04\ WT'\cos\theta}{h^2 + d^2}$$

where Q, W, h, and d are defined as before, T' is the cloud transmission and θ is the angle between the vertical and the radius vector from the burst to the ignition point. Hence,

1. See Malone (1951), Melnick and Bragg (1957), Neiburger (1949), Haurwitz (1948), Fritz (1949), Jones and Condit (1948), and Passell (1963).

Figure B-16

IGNITION RADIUS FOR BURST ABOVE CLOUDS
(horizontal receiver, nonabsorbing and nonscattering atmosphere)



NOTE: Yield = 10mt
Surface albedo = zero

SOURCE: Haurwitz (1948), Glasstone (1962) and Stanford Research Institute

$$Q = \frac{1.04\ WT'\ h}{(h^2 + d^2)^{3/2}}$$

Since T' is roughly independent of θ, Haurwitz (1948), this is a useful approximation. Because of the assumption of a nonscattering and nonabsorbing atmosphere, the results are only approximate, of course, and tend toward the upper limit of the actual ignition radii.

The much more complicated case of a burst below the clouds has been treated by Schmall (1961), also for a nonscattering and nonabsorbing atmosphere. The incident radiation on a plane (hemispherical) receiver between two parallel Lambert planes is analyzed for various plane separations and receiver altitudes. A Lambert plane, which here approximates the earth's surface and the lower surface of the cloud, is a plane for which "the reflected energy is proportional to the cosine of the angle of reflectance." Figure B-17 presents estimates of ignition radius as a function of surface and cloud albedo based on the dimensionless curves in Schmall. Note the marked increase in ignition radius for high surface albedo as the cloud albedo increases toward unity. This will be discussed below in connection with snow cover (Case III). Here again, because of the assumption of a nonabsorbing and nonscattering atmosphere and because of the assumption of perfectly flat Lambert planes, which may differ appreciably from cloud and earth surfaces, the results are only approximate and tend to be upper limits.

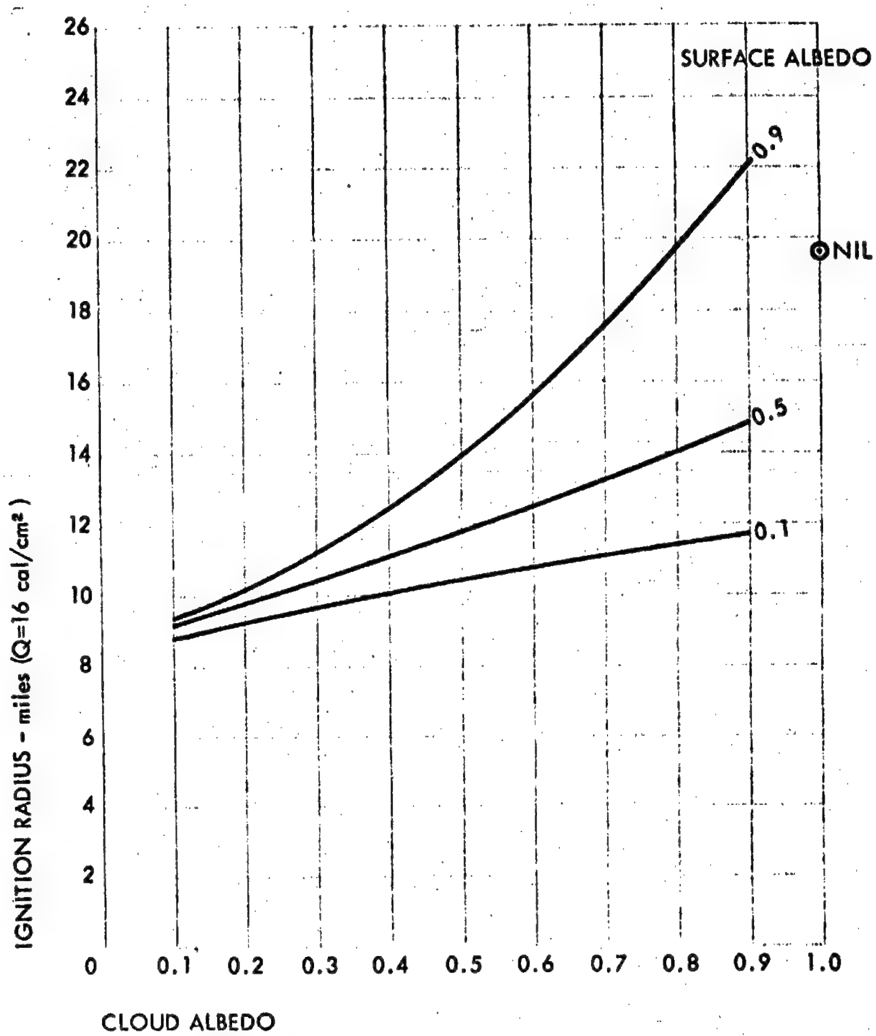
The circular symbol in Figure B-17 represents an attempt to approximate the real atmosphere case for an optimally oriented receiver. (Unfortunately, there is no convenient way to convert from optimal to horizontal receiver because of the diffuse nature of the radiation.) This was obtained by inverting the results of Cahill, et al. (1962) for the case of 100 percent surface albedo. In this reference, the transmission factor is shown as a function of both altitude and horizontal range of the receiver. A portion of one of the graphs is reproduced in Figure B-18 (after conversion of units). A plot of the intersections of the "isotransmission" lines with the horizontal axis gives the variation of transmission factor with distance from ground zero at ground level.

If a horizontal line is drawn at an altitude of 10,000 feet, for example, the intersections with this line will similarly indicate the values of transmission factor at the 10,000-foot level. However, this could also be interpreted as the ground level transmission factor below a cloud layer at an altitude of 10,000 feet, with the clouds

UNCLASSIFIED

Figure B-17

IGNITION RADIUS FOR BURST BELOW CLOUDS
(horizontal receiver, nonabsorbing and nonscattering atmosphere)



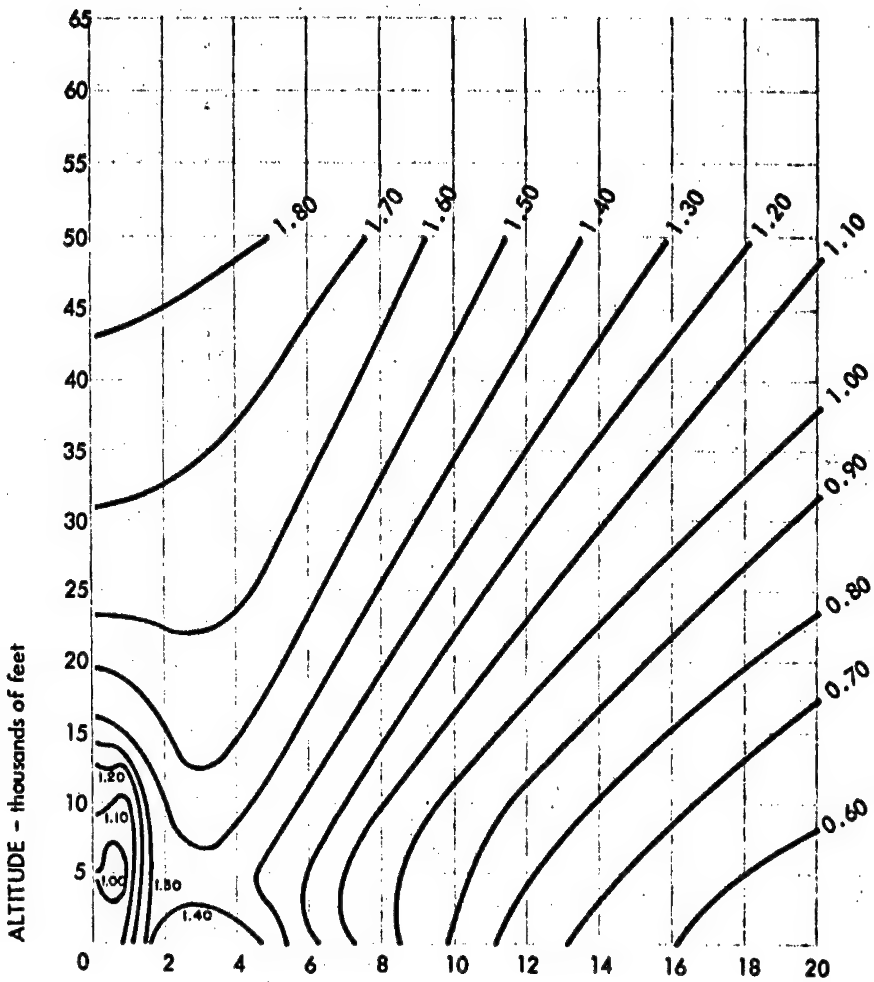
NOTE: Yield = 10mt
Burst height = 5,000 ft
Cloud height = 10,000 ft

SOURCES: Schmall (1961), Cahill, et al. (1962) and Stanford Research Institute

UNCLASSIFIED

Figure B-18

TRANSMISSION FACTOR VS ALTITUDE AND RANGE



HORIZONTAL RANGE - miles

NOTE: Burst height = 5,000 ft
Visibility = 50 miles
Surface albedo = 100 %
Precipitable water = 0.5 cm

SOURCE: Cahill at al. (1962)

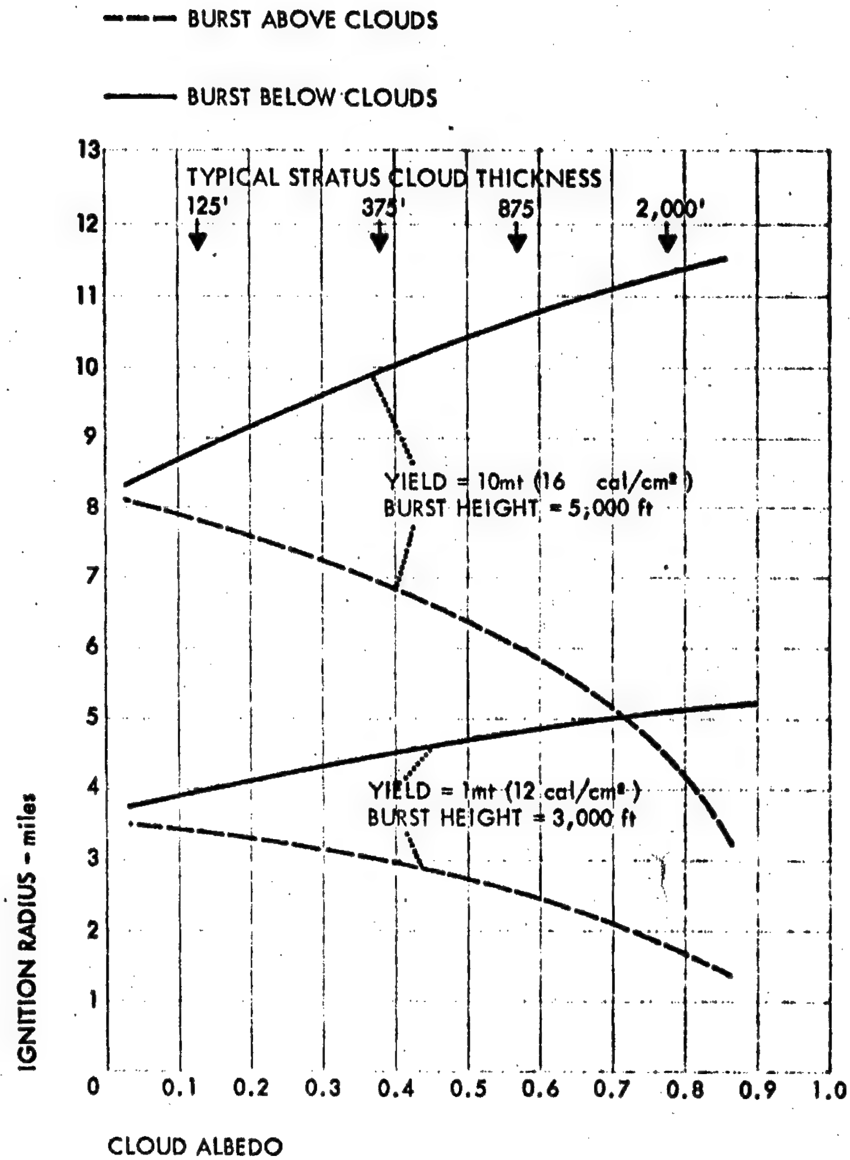
having 100 percent albedo and the surface negligible albedo. This is only an approximation, of course, since the variation of air density, water vapor density, and particulate content with altitude is thus reversed. Also, cloud albedo seldom exceeds 85 percent; see Haurwitz (1948). The results are included in Figure B-17 as an approximate indication of the importance of this case.

Figure B-19 is an attempt to evaluate the importance of the relation between burst and cloud altitude. The upper 10-mt curve is the same as the corresponding curve of Figure B-17, indicating the ignition radii for bursts below clouds. The lower 10-mt line was obtained from the lowest curve of Figure B-16 for bursts over clouds. It is based on the relationship among albedo, transmission, and absorption (their sum is equal to unity). The absorption assumed is 0.07, which is typical of Neiburger's (1949) measurements on stratus clouds. The 1-mt curves were derived in a similar fashion. If the assumption is now made that the albedo of the lower cloud surface is approximately equal to that of the upper surface, the importance of knowing whether the burst is above or below the clouds can be evaluated. This seems reasonable, at least for stratiform clouds. As an example, the ignition radius for a 10-mt burst and a cloud albedo of 0.52 (typical of altostratus from Figure B-16) varies from about 6-1/2 miles to about 10-1/2 miles, depending on whether the burst is above or below the clouds. These numbers indicate that whether the burst is above or below the clouds can make a significant difference. What this means in terms of precision in actual burst and cloud altitude differential is not known since the direct effects of the burst on the cloud are not known.

Because the fireball size is approaching the altitude dimensions of the situation being considered in Figure B-19 (a 1-mt fireball is 5,800 feet across at maximum brilliance)--Glasstone (1962)--the direct effects of the burst on the cloud may be even more important here than elsewhere. Note further that the sensitivity in terms of actual altitude variation is moderated to some extent by the variation of cloud albedo with cloud thickness. As the cloud gets thinner, slight variations of altitude can change the relative position of the burst from the center to the edge of the cloud. At the same time, the albedo of a thin cloud is less so that such a geometric variation is not so important (the figures on the horizontal axis of Figure A-10 indicate typical thickness variations for stratus clouds). Because of the potential sensitivity to relative burst and cloud height, it may be important to take into account both the dispersion of warhead fuzing altitude and the distribution of cloud height. This may be especially true for lower yield bursts (on the order of 100 kt) for which the optimum burst heights (4,000 to 5,000 feet) for low overpressures are on the order of the altitudes of typical high-albedo clouds. (An interesting technique for alleviating this sensitivity should it prove important might be the use of a cloud sensing option on the warhead fuzing system.)

Figure B-19

BURST ABOVE OR BELOW CLOUDS
(horizontal receiver, nonabsorbing and nonscattering atmosphere)



NOTE: Surface albedo 0 to 0.1

SOURCES: Neiburger (1949), Schmall (1961), and Stanford Research Institute

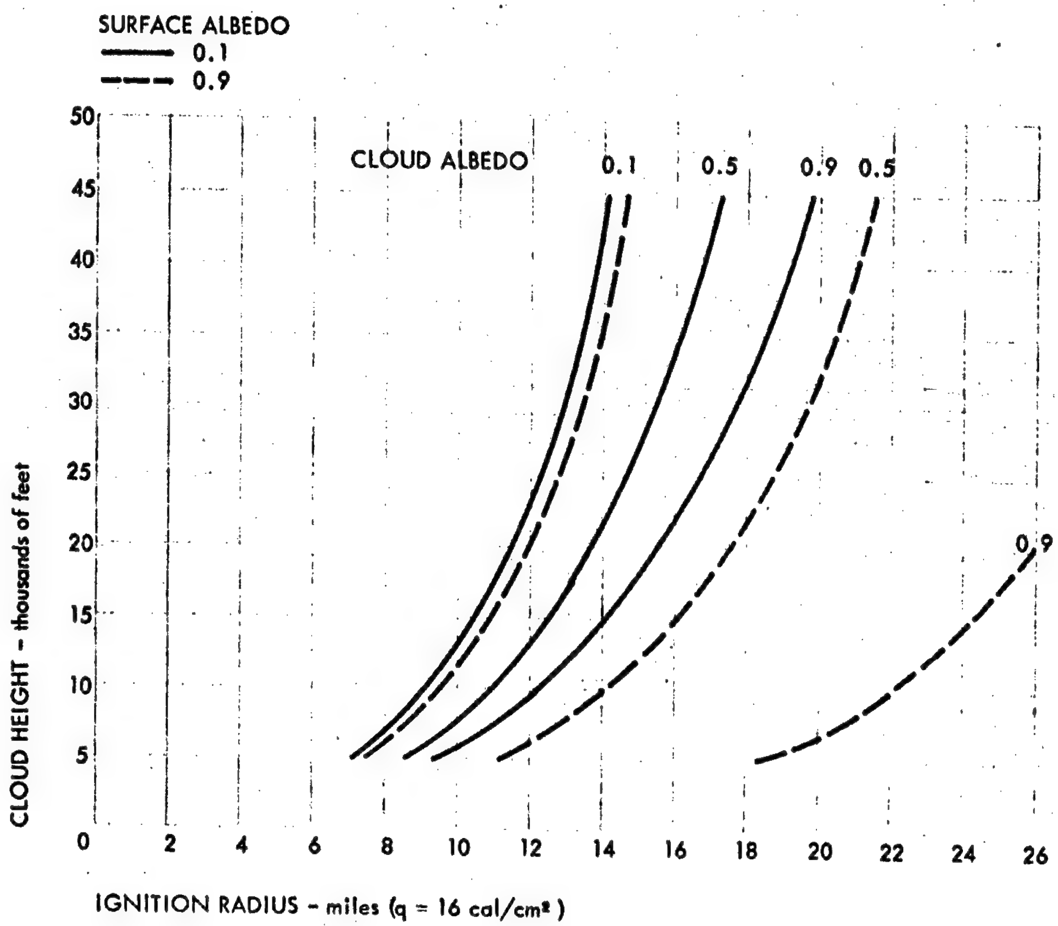
For larger yields the bursts will ordinarily be at higher altitudes, particularly if the attack is designed to maximize low overpressure radii. Figure B-20 indicates the effects of such altitude variation on ignition radius. The curves apply to the case where the burst height is equal to one-half of the indicated cloud height since no other estimates are available; see Schmall (1961). The curves are darker up to the maximum altitude at which cloud bases of the indicated albedo are likely to appear. This gives an indication of the optimum altitude for the various surface and cloud albedo conditions from the standpoint of thermal radiation incident on a horizontal receiver. Note that part of the increase of ignition radius with altitude is due to the increasing angle of incidence of the direct radiation on a horizontal receiver. This variation is approximately the same as that of the line farthest to the left on Figure B-20. The remainder of the variation arises from the increasing area of cloud from which radiation can be reflected to the receiver as the cloud height increases.

Case IV (Snow Cover). As has already been indicated by some of the previous curves, the real importance of bursts below clouds may well arise in connection with Case IV, that of snow-covered ground. In this situation both the cloud and the snow may have a high albedo so that by consecutive reflections the radiation may be transmitted much farther than it would be otherwise. Figure B-21 indicates some of the numbers involved in this case. This is a replotting of curves already shown and is in terms of ignition radius vs surface albedo. The typical values shown for surface albedo are from the Handbook of Geophysics (1960). For a cloud albedo of 0.9, for example, the ignition radius for a 5,000-foot, 10-mt burst varies from about 11-1/2 miles for the albedo of a building to about 21 miles for maximum snow albedo. Again, these figures represent upper limits (for horizontal receivers) because of the assumption of a nonabsorbing, nonscattering atmosphere. Note that aside from limestone, snow is the only surface that has an albedo higher than 0.35. The actual average albedo for a snow-covered city is not known, but in view of the large variation of ignition radius with surface albedo, it is worth investigating.

The other conditions of Case IV are also of interest. These include clear sky above snow and fog or haze above snow. Clear sky and haze conditions have been analyzed down to two miles visibility for two heights of air bursts and for surface bursts in Cahill, et al. (1962) (see Table B-II). With the exception of the single example given in Chin and Churchill (1960), there is apparently no analysis of bursts in or above moderate or dense fog (visibility $\leq$ 2 miles). Here, also, the presence of snow would increase the radiation at all ranges because of the

Figure B-20

EFFECTS OF CLOUD HEIGHT ON IGNITION RADIUS
FOR BURST BELOW CLOUDS
(horizontal receiver, nonabsorbing and nonscattering atmosphere)

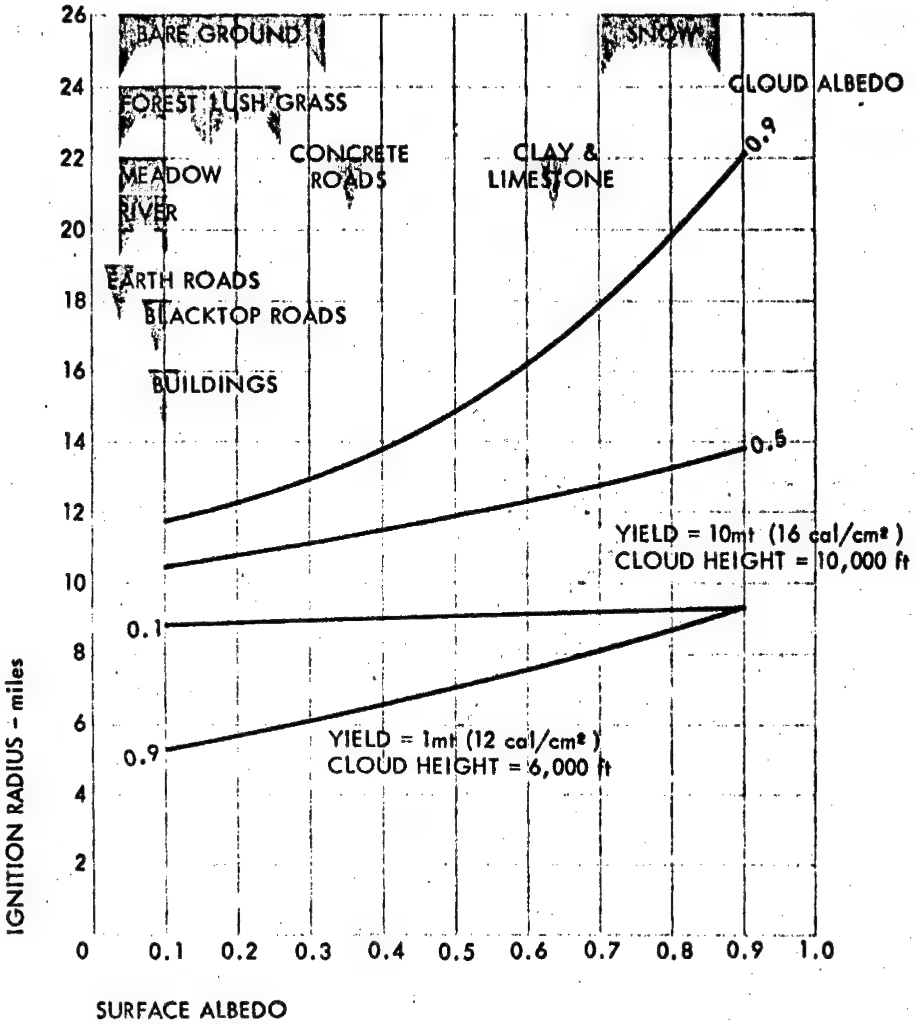


NOTE: Yield = 10mt
Burst height = 1/2 cloud height

SOURCES: Schmall (1961) and Stanford Research Institute

Figure B-21

IGNITION RADIUS VS SURFACE ALBEDO FOR BURST BELOW CLOUDS (horizontal receiver, nonabsorbing and nonscattering atmosphere)



NOTE: Burst height = 1/2 cloud height

SOURCES: Schmall (1961), <u>Handbook of Geophysics</u> (1960), and Stanford Research Institute

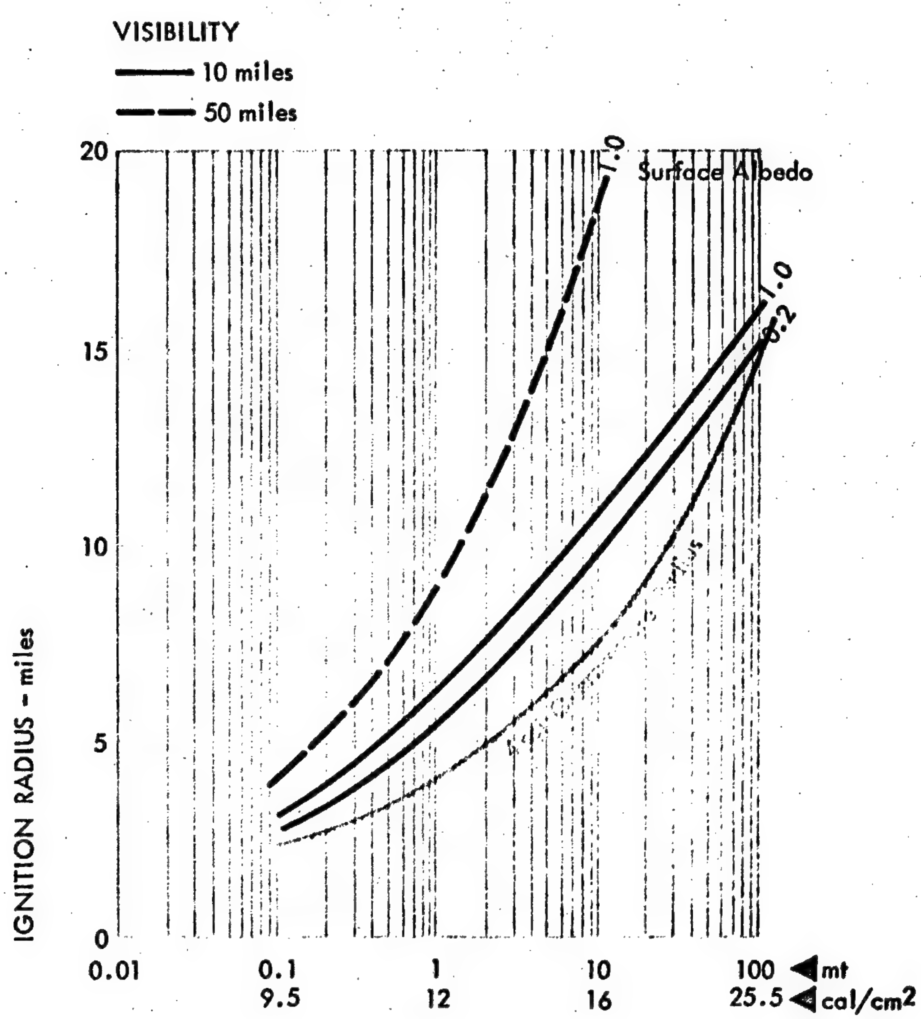
radiation scattered back into the atmosphere. A summary of the available results for a dry atmosphere derived from the transmission factors in Cahill is presented in Figure B-22 for a 5,000-foot burst. Ignition radius is plotted as a function of yield for two different visibilities and surface albedos. (The values are again given for an optimally oriented receiver and a "real" atmosphere.) Figure B-23 gives similar information for a 30,000-foot burst and shows the variation of the 4-psi radius with yield. Note that the relation between thermal radius variation and overpressure radius variation with yield changes considerably with weather condition. At 5,000-foot burst altitude, for example, they are about the same for ten-mile visibility, but for fifty-mile visibility and high surface albedo, they diverge considerably with yield. Further investigation to determine the relation between blast and thermal damage over a wide range of weather conditions would be worthwhile.

<u>Case V (Multilayer and/or Broken Clouds)</u>. One of the most likely situations involving clouds is that of multilayer and/or broken clouds (Case V). This is also the most complicated case computationally and the one with the widest variation of conditions. Here, as the sketch in Figure B-8 indicates, the problem is compounded by multiple reflections between cloud layers and from the sides of clouds and by reflections from upper layers which reach the ground through openings in lower layers. Because of the difficulties involved in a theoretical treatment, this problem is probably best approached empirically, at least for the case of bursts above clouds. As a first step, existing cloud and visibility observations could be correlated with the corresponding solar radiation observations which are obtained hourly throughout the day at many U.S. weather stations. This was done, for example, by Haurwitz (1948) at a single station for the completely overcast case previously mentioned. One problem associated with this technique is the difficulty of observing multiple cloud layers from the ground when an unbroken or nearly unbroken lower cloud layer is present. The problem is alleviated to some extent, however, by aircraft reporting and by radiosonde humidity vs altitude data. It may even be preferable in this case--for climatological purposes at least--to use the radiation records directly rather than first determining the cloud characteristics and then determining the corresponding radiation. For a burst above the clouds the ignition radius can then be determined in a manner similar to that used for Figure B-16, once the cloud transmission is known.* This method, however, would allow only a rough approximation, particularly for a single layer of broken clouds. The areas of ignition might correspond roughly to the clear areas of the sky, and the radius determined here would be that of an ignition envelope, within which scattered areas of ignition could occur.

* See Figures C-9 and C-10.

Figure B-22

IGNITION RADIUS VS YIELD AND SURFACE ALBEDO – NO CLOUDS
(burst altitude, 5,000 feet)

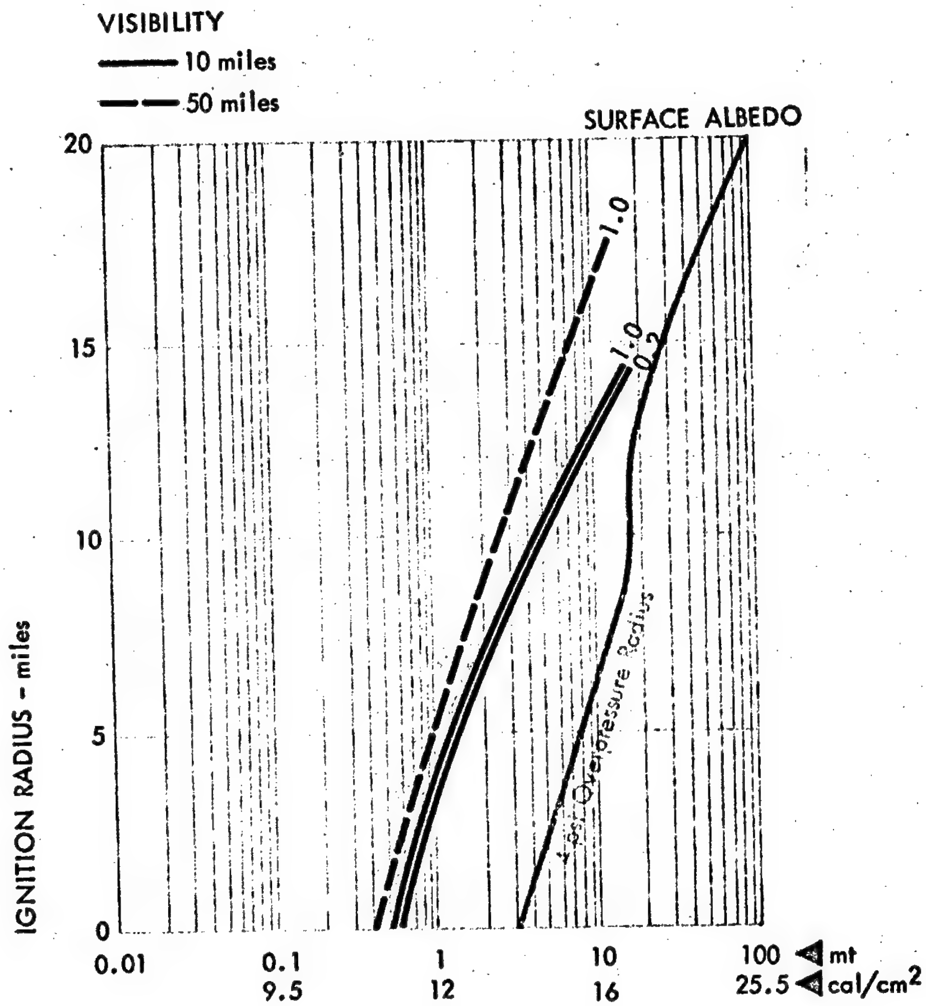


NOTE: Dry Atmosphere

SOURCES: Miller (1962), Glasstone (1962), Cahill et al. (1962), and Stanford Research Institute

Figure B-23

IGNITION RADIUS VS YIELD AND SURFACE ALBEDO— NO CLOUDS
(burst altitude, 30,000 feet)



NOTE: Dry Atmosphere

SOURCES: Miller (1962), Glasstone (1962), Cahill et al. (1962), and Stanford Research Institute

For a burst in, below, or between two cloud layers, the problem is much more complicated. Many studies have been made of the size, shape, moisture content, and albedo of clouds;* these data would be required for a detailed numerical approach to this subject. In addition, a precise analysis may require the variation of visibility with still another parameter--direction. Variations of well over 100 percent within 90° have been observed even after removing the variation caused by sun position; see Ponndorf, et al. (1952). The detail to which these variables should be incorporated into a computational model has not been determined. It would appear, however, that much additional work should be accomplished for Cases I through IV prior to any detailed computational work for this case.

The effects of meteorological conditions on atmospheric transmission can, of course, be more complicated than those described above. In all of the cases with clouds, the potential effects of rain and other precipitation should be investigated. Furthermore, eventual consideration might also be given to those conditions less likely to occur but having the potential of extremely high ignition ranges (for example, the case of a cloud bank which intersects a snow-covered hill or that of a cloud bank which lies above and extends beyond a high albedo fog). However, anything more than a cursory study of these special conditions should await the development of more definitive data for the more important cases discussed above.

The main point to be made concerning both general and specialized situations of Case V is the extreme variability possible in the location, number, and size of the initial ignition areas. Because of this variability, there will always be an appreciable uncertainty in any local or national ignition area assessment, even when the meteorological conditions are precisely known.

Summary of the Cases. To summarize the data and techniques available: For Case I (clear day) physical data and computational techniques are available for all of the conditions of interest. Actual computations have been made for only a representative set of conditions and only out to a range of 30 kilometers (18.6 miles).

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* See, for example, Neiburger (1949); Fritz (1949); Jones and Condit (1948); Serebreny and Blackmer, Reports 2 and 4 (1962); and Murgatroyd and Goldsmith; as well as the bibliography of Passell (1963).

For Case II (fog or haze) there are only limited data on distribution of particle size in fog and on fog-top albedo. Computational results exist for the burst within light fog or haze, but there are only approximate methods for bursts above the fog and no results for bursts in dense fog.

For Case III (continuous cloud cover) existing approximations can be applied for bursts above the cloud and below the cloud, but apparently none are applicable for the case of the burst within the cloud and none exist for bursts below a cloud for a real atmosphere. Furthermore, although considerable information is available on cloud shape, size, and albedo, information on droplet size distribution is inadequate for nationwide applicability. The use of radiation data could alleviate this limitation to some extent, at least for the burst above clouds.

For Case IV (snow cover) there are numerical results for the clear air and haze cases and some approximations for the case of the burst below the clouds.

Case V (multilayer and/or broken clouds) has been treated approximately for the burst above the clouds but not for any of the other conditions. Again, there is considerable information on cloud shape, size, thickness, and albedo.

In all cases (I through V) there are insufficient results to allow comparison between horizontal and optimally oriented receivers.

Figure B-24 summarizes the existing ignition radius estimates with some approximate extrapolations to various meteorological conditions, including dense fog. The values of incident radiation used are typical ignition requirements for dry pine needles:* 16 cal/cm^2 in the case of the 10-mt burst. As indicated, the ignition radius can vary from less than one mile for low visibility conditions to approximately 20 miles for the case where the visibility is 50 miles and the burst is above a surface of snow. This extreme variation makes the study of weather conditions so important in the fire problem. The estimates in Figure B-24 are presented not as absolute values but as indications of the relative importance of the various meteorological factors on atmospheric transmission. The degree to which each situation should be investigated and the range of variables of importance then involve questions of weather and climate, to be discussed in Appendix C.

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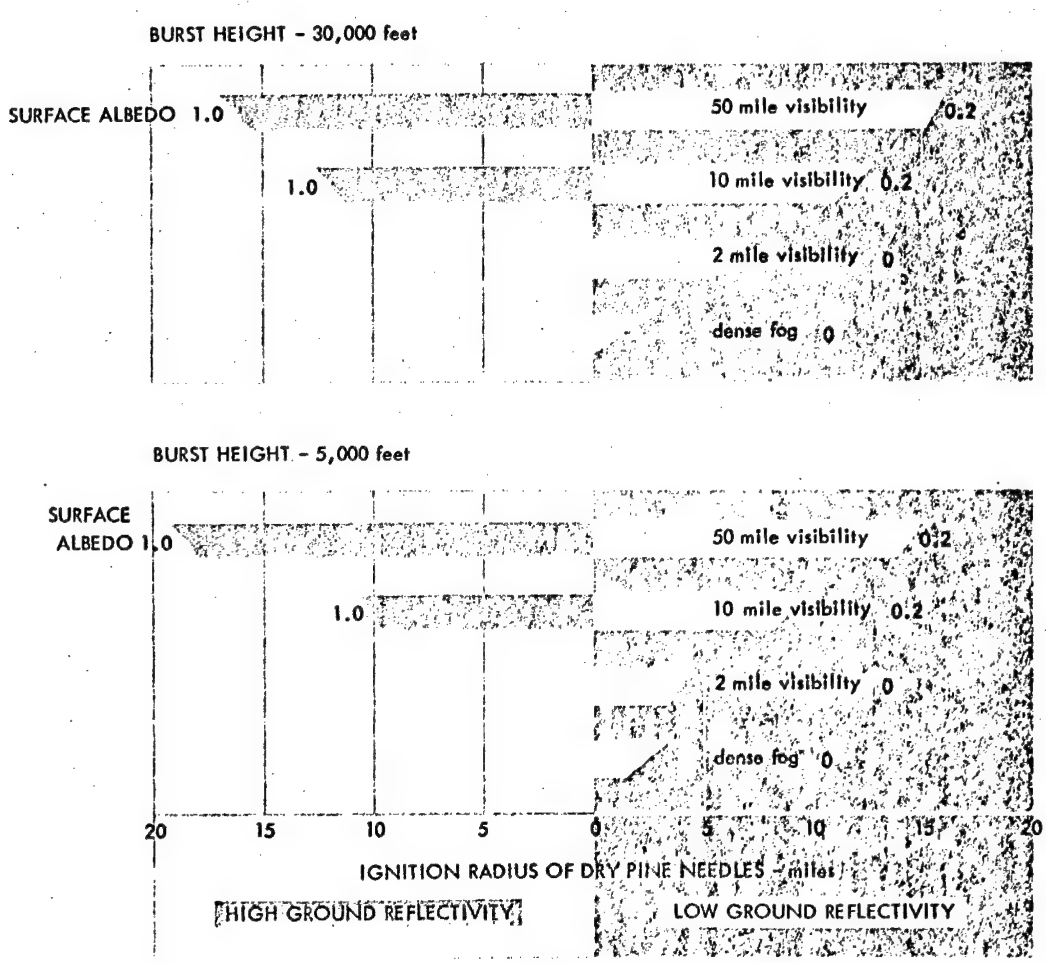
* "Dry" pine needles are interpreted to mean pine needles with an equilibrium moisture content of 0.25 percent, corresponding to a relative humidity of 10 percent. Note that the direct effect of the atmosphere on the moisture condition of the pine needles is not included.

Figure B-24

SUMMARY OF IGNITION RADIUS ESTIMATES FOR VARIOUS METEOROLOGICAL CONDITIONS
(cloudless day, optimally oriented receiver, real atmosphere)

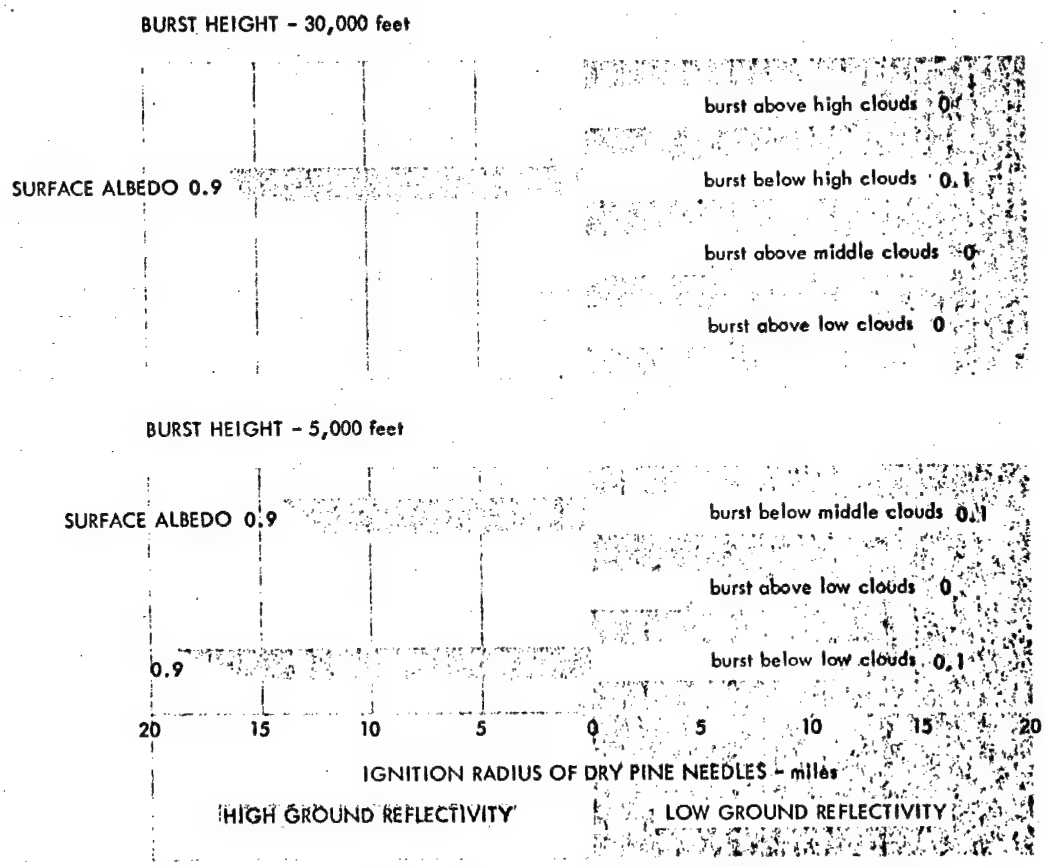


YIELD: 10 mt (using ignition requirements from Glasstone (1962) and Miller (1962)
35 mt (using ignition requirements from Martin (1959)

SOURCE: Cahill, et al (1962) and Stanford Research Institute

Figure B-24 (Continued)

SUMMARY OF IGNITION RADIUS ESTIMATES FOR VARIOUS METEOROLOGICAL CONDITIONS
(overcast day, horizontal receiver, nonabsorbing and nonscattering atmosphere)



YIELD: 10 mt (using ignition requirements from Glasstone (1962) and Miller (1962)
35 mt (using ignition requirements from Martin (1959)

SOURCE: Schmall (1961), Haurwitz (1948), Neiburger (1949), and Stanford Research Institute

Influence of the Topography in the Target Area

In addition to the modification of the thermal pulse by the effects of weather, the topography of the area surrounding the target will influence the final thermal flux on the target. This effect of topography has not been considered in relation to thermal energy from nuclear weapons although considerable attention has been directed to the effects of topography on the blast wave; see Nuclear Weapons Blast Phenomena (1960).

If a hill or mountain is situated between a nuclear detonation and a target, the direct rays from the bomb obviously will be stopped. In addition, the amount of diffused rays which strike the target will depend critically on the weather. In a heavy fog, for instance, the thermal energy will be entirely diffused with the energy falling on the target independent of its position in relation to the hill mass. This conclusion has been borne out by experiments of Paszynski (1959), which show that in a heavy fog it is impossible to detect the direction of the sun--that radiation from all directions is equal. Quantitatively, this means that the index computed in the study (diffuse sunlight/total sunlight) becomes equal to unity under conditions of heavy atmosphere.

If the albedo of a hillside is high (for example, the hill is covered with snow) and the target area lies between the hill and the detonation, it is obvious that the reflection from the hill may significantly increase the total energy falling on the target area. Furthermore, the thermal energy will no longer come from a single predominant direction, particularly on a day when the visibility is high. Further information or references to the effects of topography on the thermal pulse are unknown.

Interaction of the Thermal Pulse with the Target Complex

As with any radiant energy, the initial thermal pulse from a weapon may either be absorbed by, reflected from, or transmitted through a target. The energy which is absorbed by the target element or transmitted through it may ignite or otherwise damage this element. The reflected and transmitted energy may fall on other target elements before it is ultimately absorbed. Hence, it is important to consider not only the effect of energy on a target, but the effect of the target on the thermal pulse. The final intensity impinging on a target element will be a certain fraction (possibly greater than unity) of the intensity which would have been received if the target had been in the open with no shielding or reflections by other elements. This is defined as a transmission factor of the target complex (see the discussion on page B-16.)

In this section both the direct effects of the thermal pulse on the target and the modification of the pulse by the target will be considered.

The elements of a target may be treated individually or they may be aggregated. The following is a listing of most of the targets considered in this study.

- Units
  - Materials
  - Life system units
    - Human
    - Animal
    - Vegetation
  - Materiel system units
    - Structures
- Aggregates
  - Districts
  - Cities
  - States
  - Regions
  - National
  - Crops
  - Forests

Orientation of the Target. A factor which is often ignored but applies to all targets is the orientation of the target to the fireball. The variation of thermal flux with range, as given in Equation (5), assumes that the radiation is emitted from a source point and falls on the surface of a sphere whose center coincides with the source. The fireball is not homogeneous, however, and hence the source of radiation cannot be considered as concentrated at one point. Since the error in making this assumption is not serious, it has been ignored in this paper.*

The assumption that the energy falls on a surface normal to a line drawn from the target to the fireball is a serious one, and target orientation must be included in any valid calculations or estimates of the fire threat. Miller (1962) has considered the orientation of the

* Hillendahl (1959, Vol. I) considers the case of the inhomogeneous fireball.

target from a purely geometric point of view. The development in the present study, however, will be slightly different.

Assume that the fireball is spherical and a homogeneous radiator, an assumption which applies fairly well for all but outer space shots. Let $\bar{R}$ be the vector from the target to the fireball, but let $\bar{n}$ be the vector normal to the surface of the target. Then, the energy flux must be modified by the term

$$\frac{\bar{R} \cdot \bar{n}}{|\bar{R}| \cdot |\bar{n}|} = \cos \theta ,$$

where θ is the angle between the two vectors. If $\bar{R}$ is divided into its components from the target to ground zero and from ground zero to the fireball center, then

$$\bar{R} = \bar{r} + \bar{h} ,$$

where $\bar{r}$ is the horizontal component of $\bar{R}$, and $\bar{h}$ is the vertical component. Hence, $\cos \theta$ becomes

$$\cos \theta = \frac{(\bar{h} + \bar{r}) \cdot \bar{n}}{|\bar{h} + \bar{r}| \cdot |\bar{n}|} = \frac{h \cos \alpha + r \cos \beta}{\sqrt{h^2 + r^2}}$$

where α is the angle between $\bar{n}$ and the vertical and β is the angle between $\bar{n}$ and the projection of $\bar{R}$ on the earth's surface. This gives a final correction for the thermal energy as

$$Q = \frac{ET(h \cos \alpha + r \cos \beta)}{4\pi(h^2 + r^2)^{3/2}} = \frac{ET (\sin \phi \cos \alpha + \cos \phi \cos \beta)}{4\pi R^2}, \quad (22)$$

where ϕ is the elevation angle of the fireball viewed from the target. When the surface is horizontal, (22) reduces to (22h):

$$Q = \frac{ET}{4\pi R^2} \sin \phi . \quad (22h)$$

When the surface is vertical, (22) reduces to (22v):

$$Q = \frac{ET}{4\pi R^2} \cos \phi \cos \alpha . \qquad (22v)$$

For the case of detonations outside the atmosphere, the geometry is somewhat more complicated because the fireball is no longer a sphere but is pancake-shaped. The effect of target orientation has not been calculated for this case.

The following paragraphs are concerned with the interaction of the components of a target complex and the thermal pulse. This section will review only the direct effects made by the nuclear thermal pulse on a target; secondary effects will not be considered. As an illustration, the thermal energy may ignite dead leaves or other refuse on the floor of a forest; this in turn could cause the ultimate destruction of the entire area. But only the radiation requirement for the initial ignition of the leaves would be considered here.

Response of Materials to the Thermal Pulse. The impingement of a nuclear thermal pulse on materials may manifest itself in any one of a number of different ways. These effects range between the two extremes of (1) no damage to the materials and (2) a sustained flaming. Other possibilities are charring without ignition, transient flaming which disappears at the end of the thermal pulse, or destruction of the material by sustained glowing. (Plastics when irradiated may melt, crack, smoke, or flame.) Transient flaming may occur with a high-energy, short-time pulse. In this phenomenon, the outer layer of the material may vaporize and ignite without further damage to the lower layers. For example, transient flaming will occur when heavy, dark cotton draperies are exposed to a 10-kt weapon at a range of one mile; see Figure B-43.

From the standpoints of the ignition of widespread fires and of fire spread, the most important effect on a material is sustained flaming. However, if the material is near combustibles, transient flaming is obviously important; if it is on the floor of a forest, a sustained glowing may be critical. All of these reactions may take place in the so-called kindling fuels, that is, thin nonconductors. Before discussing this most important class of fuels, a few remarks will be made concerning the reaction of thick nonconductors, plastics, and materials treated with flame retardants (which must not be confused with materials treated to protect against the high radiation flux of a

nuclear weapon). Special materials and coatings designed to counter intense thermal radiation from nuclear weapons will be considered in Appendix E.

For most applications, damage by radiant energy is assumed to be dependent on the attainment of a certain critical temperature. Therefore, the prediction of depth of damage requires a knowledge of the maximum temperature attained at each depth as the thermal energy absorbed at the surface diffuses into the solid. In thick pieces of wood, for example, up to a temperature of about 230°-240°F, the moisture in the wood is driven off. The loss of moisture is the greatest between 212°-230°F; see Bomb Damage Analysis (1949). At 300°F, a chemical decomposition of the wood fibres occurs. A darkening of the surface of the wood is perceptible at this temperature and increases as the temperature rises. At 520°F, complete decomposition of the wood occurs without further application of external heat. This last phase is commonly ascribed to the initiation of a strongly exothermic reaction.

Much effort has been placed on the measurement of temperatures created by nuclear thermal pulses within thick nonconductive materials; see The Thermal Data Handbook (1954). Since the radiation damages the material but seldom leads to a sustained ignition, only the summarized results will be presented here. The data are directly abstracted from The Thermal Data Handbook and shown in Figures B-25, B-26, and B-27; Table B-III lists the important parameters required to use the figures.

Because of their shatterproof characteristics, certain plastics have obvious advantages over glass for use as glazing, window covering, skylighting, and awning materials in the construction of homes and industrial buildings. Furthermore, in some test shots, homes equipped with plastic window curtains and other plastic items were less subject to interior ignitions than those using other fabrics.

In Operation TEAPOT--Laughlin (1957)--680 plastic samples were installed at ranges from 6,600 feet to 8,690 feet from ground zero. In addition, numerous plastic articles were placed inside buildings. The plastics were representative of all types widely used on the consumer market. The general conclusions drawn were that the results of the thermal action were influenced by the type of material, its thickness, and its color. Thermoplastics were more affected than thermosetting plastics. In general, the vinyls suffered more than other samples submitted.

More quantitative results regarding the reaction of plastics have been discovered in laboratories. Results derived at the Naval

Classified Figures B-25, B-26, and B-27 pertaining to pulse irradiation have been deleted.

Notes to classified Figures B-25, B-26, and B-27 have been deleted.

Table B-III

THERMAL PROPERTIES OF MATERIALS
April 15, 1954

Material	Density, ρ (g/cc)	Specific Heat, c (cal/g-°C)	Conductivity, k (cal/sec-cm-°C)	Diffusivity, h (sq cm/sec)
Insulating				
Air	9.46×10^{-4}	0.24	0.55×10^{-4}	0.22
Asbestos	0.58	0.20	4.6×10^{-4}	40×10^{-4}
Balsa	0.12	0.4	1.2×10^{-4}	25×10^{-4}
Brick (common red)	1.8	0.2	16×10^{-4}	18×10^{-4}
Celluloid	1.4	0.35	5.0×10^{-4}	10×10^{-4}
Cotton, sateen, green	0.70	0.35	1.5×10^{-4}	2.5×10^{-4}
Fir, Douglas				
Spring growth	0.29	0.4	2×10^{-4}	17×10^{-4}
Summer growth	1.00	0.4	5×10^{-4}	12×10^{-4}
Fir, white	0.45	0.4	2.6×10^{-4}	14×10^{-4}
Glass, window	2.2	0.2	19×10^{-4}	43×10^{-4}
Granite	2.5	0.19	66×10^{-4}	140×10^{-4}
Leather sole	1.0	0.36	3.8×10^{-4}	11×10^{-4}
Mahogany	0.53	0.36	3.1×10^{-4}	16×10^{-4}
Maple	0.72	0.4	4.5×10^{-4}	16×10^{-4}
Oak	0.82	0.4	5.0×10^{-4}	15×10^{-4}
Pine, white	0.54	0.33	3.6×10^{-4}	18×10^{-4}
Pine, red	0.51	0.4	5×10^{-4}	24×10^{-4}
Rubber, hard	1.2	0.5	3.6×10^{-4}	60×10^{-4}
Teak	0.64	0.4	4.1×10^{-4}	16×10^{-4}
Metals (100°C)				
Aluminum	2.7	0.22	0.49	1.0
Cadmium	8.65	0.057	0.20	0.45
Copper	8.92	0.094	0.92	1.1
Gold	19.3	0.031	0.75	1.2
Lead	11.34	0.031	0.081	0.23
Magnesium	1.74	0.25	0.38	0.87
Platinum	21.45	0.027	0.17	0.29
Silver	10.5	0.056	0.96	1.6
Steel, mild	7.8	0.11	0.107	1.2
Tin	6.55	0.056	0.14	0.38
Miscellaneous				
Ice (0°C)	0.92	0.492	54×10^{-4}	120×10^{-4}
Water	1.00	1.00	14×10^{-4}	14×10^{-4}
Skin (porcine, dermis, dead)	1.06	0.77	9×10^{-4}	11×10^{-4}
Skim (human, living, averaged for upper 0.1 cm)	1.06	0.75	8×10^{-4}	30×10^{-4}
Polyethylene, black	0.92	0.55	8×10^{-4}	17×10^{-4}

SOURCE: *The Thermal Data Handbook* (1954).

Material Laboratory are shown in Table B-IV. These data should only be used as approximate measures of the comparative susceptibilities of the various plastics to thermal damage. The Effects of Nuclear Weapons, Glasstone (1962), summarizes the results of thermal radiation on plastics by stating:

> ". . .many plastic materials, such as Bakelite, cellulose acetate, Lucite, Plexiglas, polyethylene, and Teflon, have been found to withstand thermal radiation remarkably well. At least 60 to 70 calories per square centimeter of thermal energy are required to produce surface melting and darkening."

Finally, it should be pointed out that the products of combustion of a plastic may be extremely toxic or chemically active. Comprehensive studies of this problem have not been made, but the subject is of obvious importance since plastics are used extensively in home building and furnishing.

In addition to the aforementioned research on plastics, the Naval Material Laboratory has done considerable work on the susceptibility to damage of many other types of materials. The results of these studies are reported in publications of the Naval Material Laboratory and in The Thermal Data Handbook. One interesting result concerned treatment of materials with flame retardants. It was concluded that flame retardant treatment increased resistance to destruction only for woolen fabric. For white cottons, on the other hand, resistance to destruction was reduced, presumably as a result of increased absorptance. However, there was no self-propagating flaming or afterglow of treated fabrics and when destroyed they formed a brittle mat of carbonized fibers.

These general results on flame retardant treated fabrics agree with more recent British tests described in Evans (1960). These tests showed that although the flame-proofed fabric is not destroyed by flaming, it loses strength at a lower heat dose than does the untreated fabric, in a range below the point where the latter flames; see Table B-V.

By far the greatest amount of effort, both in the laboratory and in weapons tests, has been directed to the ignition of kindling fuels by thermal pulses. Fortunately, the bulk of all ignitable substances in any target area are composed of cellulosic fuels, and standardized cellulose can be used in many experiments. In this paper, the results derived at the Naval Radiological Defense Laboratory (NRDL) will be considered in some detail. Most of the work has been done with cellulosic fuels and square wave pulses although extensions have been made to other conditions.

Table B-IV

CRITICAL ENERGIES FOR THERMAL DAMAGE TO PLASTIC MATERIALS

Material	Effect	Critical Energy (cal/sq cm)
Plastic Materials[a]		
Cellulose acetate (transparent), 1/8"	Surface melting	67
	Blackening of back surface	170
Fabric base phenolic, FBG (opaque), 1/8"	Surface browning	5.5
	Flaming	18
Melamine asbestos (opaque), 1/8"	Dense smoking	23
	Flaming	63
Melamine glass, GMG (opaque), 1/8"	Slight scorching	23
	Charring	44
Paper base phenolic, PBE (opaque), 1/8"	Surface browning	4.5
	Flaming	17
Polyester glass (opaque), 1/8"	Flaming, browning	61
Polyester Paraplex, 5% styrene, 1/8", P-43 (transparent)	Cracking and splitting	150
Polyethylene (opaque), 1/8"	Surface melting	67
	Persistent flaming	160
Vinylite 5544 (opaque), 1/8"	Surface blackening	1.8
	Dense smoking	3
	Flaming	27
Vinylite 5900 (opaque), 1/8"	Surface blackening	2
	Dense smoking	3
	Flaming	13
Vinylite 50517 (opaque), 1/8"	Surface browning	6
	Dense smoking	13
Window Plastics[b]		
Cellulose acetate butyrate 19078, 1/8"	Surface melting	60
	Destruction	200
Diallyl glycol carbonate 14598, 1/4"	Surface melting	90
	Destruction	290
Heat resistant methyl methacrylate 15987, 1/4"	Surface melting	70
	Bubbling	270
Laminated methyl methacrylate 18503, 1/2"	Surface melting	60
	Bubbling	300
Laminated methyl methacrylate 18521, 1/2"	Surface melting	70
	Bubbling	220
Laminated methyl methacrylate 18765, 1/2"	Surface melting	70
	Bubbling	300
Laminated heat resistant methyl methacrylate 19873, 1/2"	Surface melting	90
	Bubbling	300
Methyl methacrylate 15978, 1/4"	Surface melting	70
	Bubbling	280
Polyester 18368, 1/4"	Surface melting	110
	Destruction	270
Polymethyl alpha chloracrylate 18212, 1/4"	Surface melting	84
	Destruction	250
Unidentified 19315, 1/8"	Surface melting	40
	Bubbling	95
Vinyl copolymer 19077, 1/8"	Surface melting	20
	Destruction	200

[a] Plastic materials submitted by the Bureau of Ships and tested at NML, using a carbon arc source at an irradiance of 85 cal/sq cm-sec. Critical energies are accurate within ±15% limit of error.

[b] Various transparent Air Force window plastics for which progressive effects of thermal radiation were as follows: surface melting, formation of small bubbles leading to opacification, deep melting, blackening, and flaming. Not all effects were seen in all plastics.

SOURCE: *The Thermal Data Handbook* (1954).

Note: Initial surface melting, which was not readily observed with the naked eye, was discerned by means of a shadometer. Above 100 cal/sq cm the effect of invisible deposits of dust particles was to increase markedly the damage to the clear plastics. It is expected, therefore, that scratches and surface contamination may decrease the resistance of these plastics to high intensity thermal radiation. Field tests at Operation Snapper confirm the resistance of AF plastic canopies to thermal radiation, but quantitative estimates for operational use are difficult to make at present. Absorption of infrared radiation by clear plastics implies that spectral characteristics of the radiation are of utmost importance.

Table B-V

CONSTANT FLUX FALLING ON SAMPLES
(10.0 cal/cm^2 sec)

Exposure (seconds)	Thermal Dose (calories)	Bursting Strength of 4-inch Diameter Area (psi)	
		Untreated Poplin	F/P[a] Poplin
1.0	10	Sample ignited	Sample charred to destruction
0.9	9	<5.0	--
0.8	8	30.9	<5.0
0.7	7	40.3	18.2
0.6	6	40.0	31.1
0.5	5	40.5	35.5
Unexposed	0	40.0	36.0

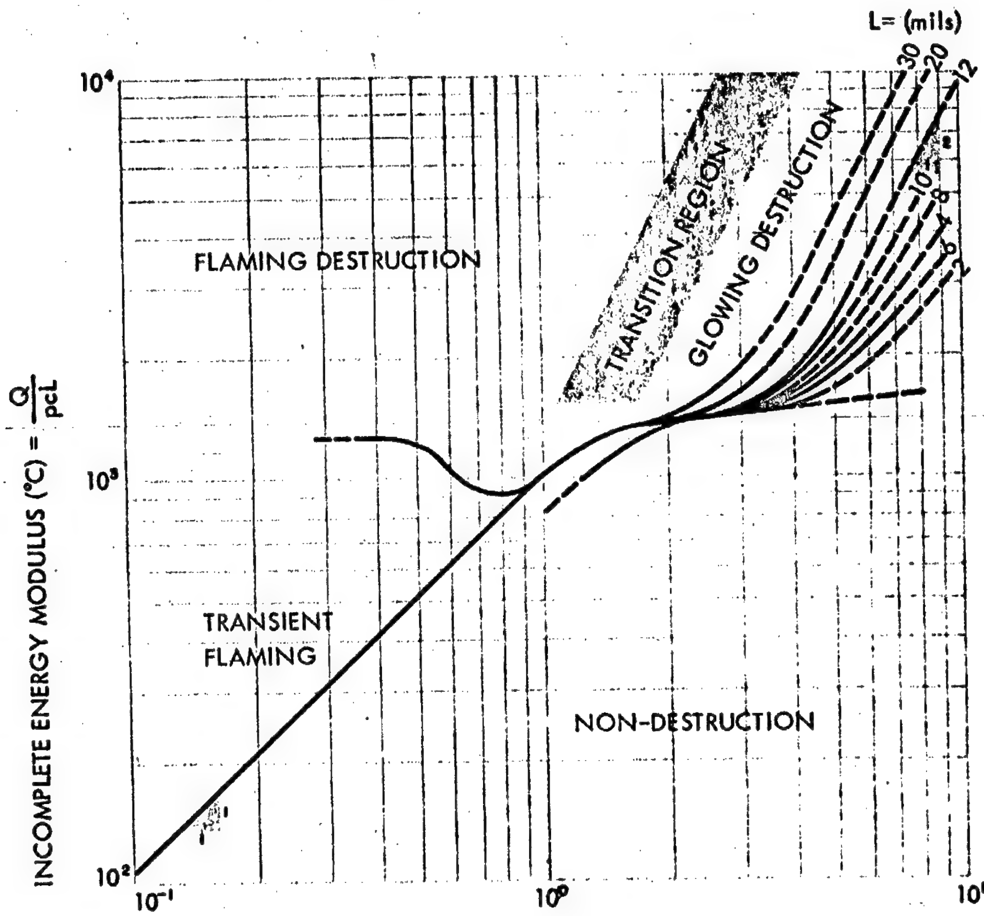
a. Fireproofed.

Source: Evans (1960).

Figure B-28 shows the first basic NRDL results for the ignition of cellulosic materials by square wave pulses of time duration t_s and total energy Q; see Butler, et al. (1956). The constants appearing in the variables are dependent only on measurable properties of the material: L = thickness of the material in cm, ρ = density in gm/cm^3, c = specific heat capacity in cal/deg/gm, and α = the thermal diffusivity (thermal conductivity/ρc) in cm^2/sec. The curves in Figure B-28 apply only to blackened materials (absorptivity, 90 percent) with an equilibrium moisture content of 5 percent (relative humidity, approximately 40 percent). Because of these restrictions, they have only limited direct interest here. The importance of the results, however, is that they show that the properties of flaming, glowing, and transient flaming actually can be related analytically to properties of a material, the total calories/cm^2 impinging on the material, and the duration of the square wave pulse.

Figure B-28

REACTION OF CELLULOSE TO HIGH INTENSITY THERMAL PULSE (square wave)



$\sqrt{\text{FOURIER MODULUS*}} = \sqrt{\frac{a t_s}{L^2}}$

* dimensionless

$T_o = 298 \pm 25°$ K

Equilibrium moisture content =5%

SOURCE: Butler et al. (1956)

The next important step in fire research was to determine whether or not a similar relationship would hold for a different pulse shape; Martin and Lai (1958). The following reasoning was used in setting up the experiment. In Figure B-28 the abscissa is seen to be a function of $\alpha t_s/L^2$ which is dimensionless. The time scaling equation for the weapon pulse in Figure A-11 shows that the time to the maximum power is proportional to the square root of the yield, i.e.,

$$t_{max} \approx W^{1/2} .$$

Hence, for the dimensions to be similar, the abscissa should probably be a function of $\alpha t_{max}/L^2 = \alpha W^{1/2}/L^2$.

A limited number of laboratory tests on materials were made, using thermal pulses of the same shape as those shown in Figure A-11, but varying in intensity and duration. It was found that if $Q/\rho Lc$ were plotted as a function of t_{max}/L^2, regions for various types of ignition were clearly defined by the data. The curves separating the regions were, however, of somewhat different shape. The authors conclude that

> ". . .no simple square-wave weapon pulse equivalence is found for ignition, but it can be stated that equivalent effects are observed for weapon pulses having peak irradiance* of about three times the irradiance level of the square-wave input; sustained flaming ignition at the higher irradiances requiring up to <u>40 percent less</u> energy and sustained glowing requiring up to <u>a third more</u> energy when delivered in the form of the simulated weapon pulse."

The above completed the NRDL experiments on the effect of pulse shape.** The next step was to investigate the effects of varying the absorptivity (energy absorbed/energy impinging) and moisture content of the material; see Martin, et al. (1958). It was found that absorptivity of the material acts merely as a multiplicative factor for the energy required for ignition. As an example, if 12 calories/cm^2 were required

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* Cal/cm/sec = power per square centimeter.

** Other agencies have done many tests on materials using square, triangular, and other weapon simulated pulse shapes. The theory relating the square shape to the actual weapon pulse is well developed for <u>thick</u> materials in the <u>Thermal Data Handbook</u> (1954).

to ignite a material with absorptivity = 0.9, it would require $(0.9/0.4) \times 12 = 27$ calories/cm^2 to ignite a material with absorptivity 0.4, all other conditions being equal.

The results for varying the moisture content are somewhat more complex. In the report of Martin, et al. (1959), the combined results of experiments with moisture content, simulated pulse shapes, absorptivity, and other properties of the cellulosic materials are given in Figures B-29 and B-30. Table B-VI lists the values of the parameters for some kindling fuels. Here, m is the moisture content of the material; to correct the ordinate for moisture, the values given in the figures must be multiplied by

$$\frac{1 - 3.2m}{1 + 3.2m_{nominal}} \tag{23}$$

Figures B-31 through B-38 show the resultant reponses of the materials listed in Table B-VI under conditions of nominal moisture content.

A few important facts should be pointed out concerning the experiments made on the response of materials.

1. By statistical tests, the results are considered reliable and reproducible under the conditions assumed.

2. There is a yield, W_e, which is most efficient in producing fires (see Figure B-29 and B-30). In terms of the properties of the material, this yield is given by

$$W_e(\alpha/L^2)^2 = 3.5$$

or

$$W_e = 3.5(L^2/\alpha)^2 \ . \tag{24}$$

In Figures B-33 and B-34, for example, this yield is at about 3 kt for pine needles (weathered). A smaller yield for the same calories per unit area, Q, will cause transient flaming only; any larger yield with the same Q will cause no damage at all.

UNCLASSIFIED

Table B-VI

MATERIALS AND THEIR PROPERTIES[a]

Material	Weight (oz/yd)	Thickness (in.)	Thickness, L (cm)	Density ρ (gm/cm^3)	Thermal Diffusivity, α (cm^{2}sec^{-1} x 10^{-3})	$(\alpha/L^2)^2$ (sec^{-2})	Absorptance, a (dimensionless)	$\frac{a}{\rho L c_o}$ (cgs)	Moisture Content		
									m (10%RH)	m (nom)	m (90%RH)
Newspaper, single sheet, medium printed areas	1.5	0.0032	0.0081	0.62	0.94	205	0.6	343	0.03	0.07	0.15
Newspaper, single sheet, dark areas	1.5	0.0032	0.0081	0.62	0.94	205	0.8	457	0.03	0.07	0.15
Kraft corrugated board, first thickness	6	0.013	0.032	0.66	0.95	0.93	0.7	98	0.025	0.05	0.12
Heavy cotton drapery, dark color	13	0.033	0.082	0.55	0.92	0.0188	0.7	46	0.025	0.05	0.12
Window shade material, creme color	6	0.0084	0.021	0.9	1.02	5.35	0.4	66	0.005	0.01	0.03
Wool pile upholstery material, dark color	15	0.040	0.10	0.5	0.9	0.0081	0.8	48	0.025	0.05	0.12
Walnut leaves, fallen weathered	3	0.006	0.015	0.65	1.6	50.5	0.7[b]	216	0.025	0.05	0.12
Pine needles, weathered	--	0.016	0.04[b]	0.54[b]	1.66[b]	1.06	0.6	81	0.025	0.05	0.12
Beech leaves, fallen weathered	1	0.0036	0.009[b]	0.39[b]	1.8[b]	494	0.6	513	0.025	0.05	0.12
Harding grass, dried	1.7	0.006	0.015[b]	0.39[b]	1.8[b]	64	0.5[b]	257	0.025	0.05	0.12
Heavy military canvas, olive green	18	0.028	0.070	0.87	1.01	0.042	0.9	46	0.005	0.01	0.03
Wool serge material, olive drab	16	0.024	0.060	0.91	1.0	0.077	0.7	38	0.025	0.05	0.12

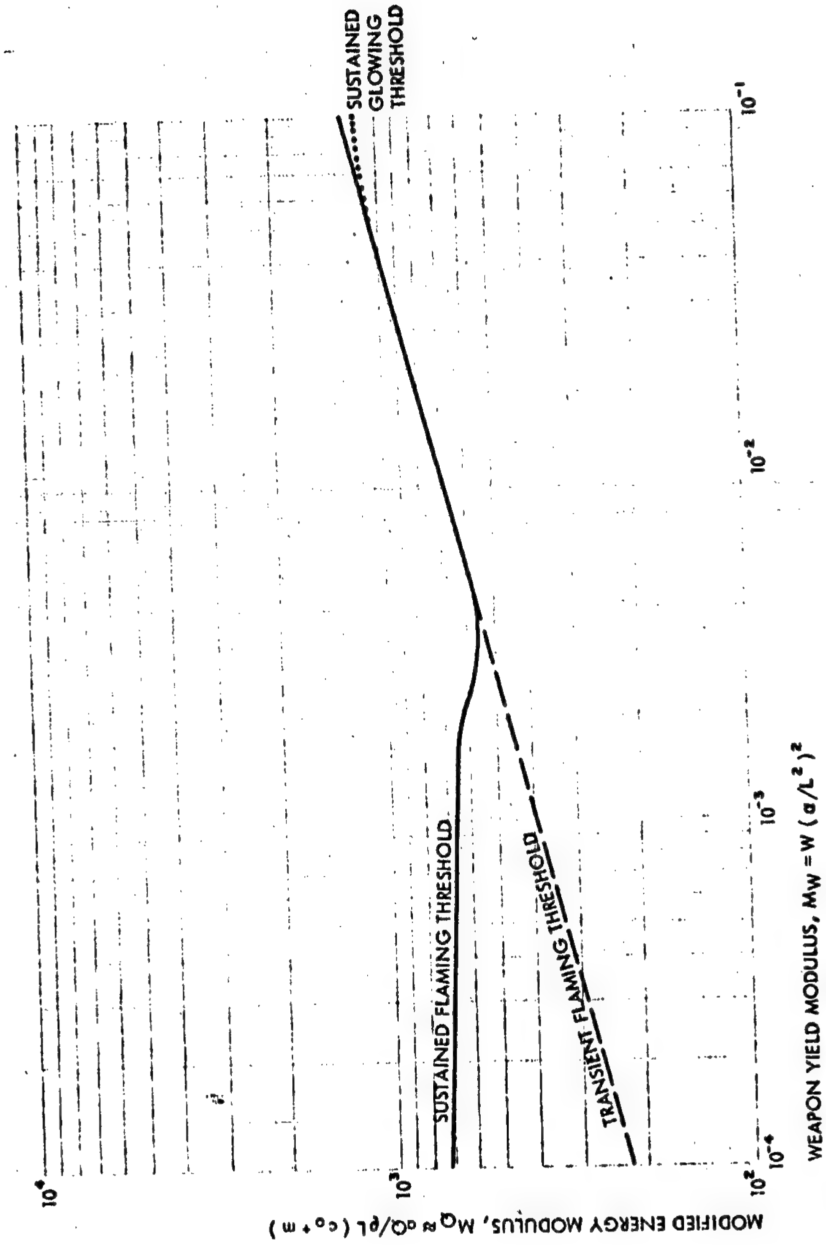
[a] The dry (10% RH) specific heat, C_o, is assumed to be 0.31 cal deg^{-1} gm^{-1} for all materials. Nominal humidity is taken as 40% RH.
[b] Byram, *et al.* (1952).

SOURCE: Martin, *et al.* (1959).

UNCLASSIFIED

Figure B-29

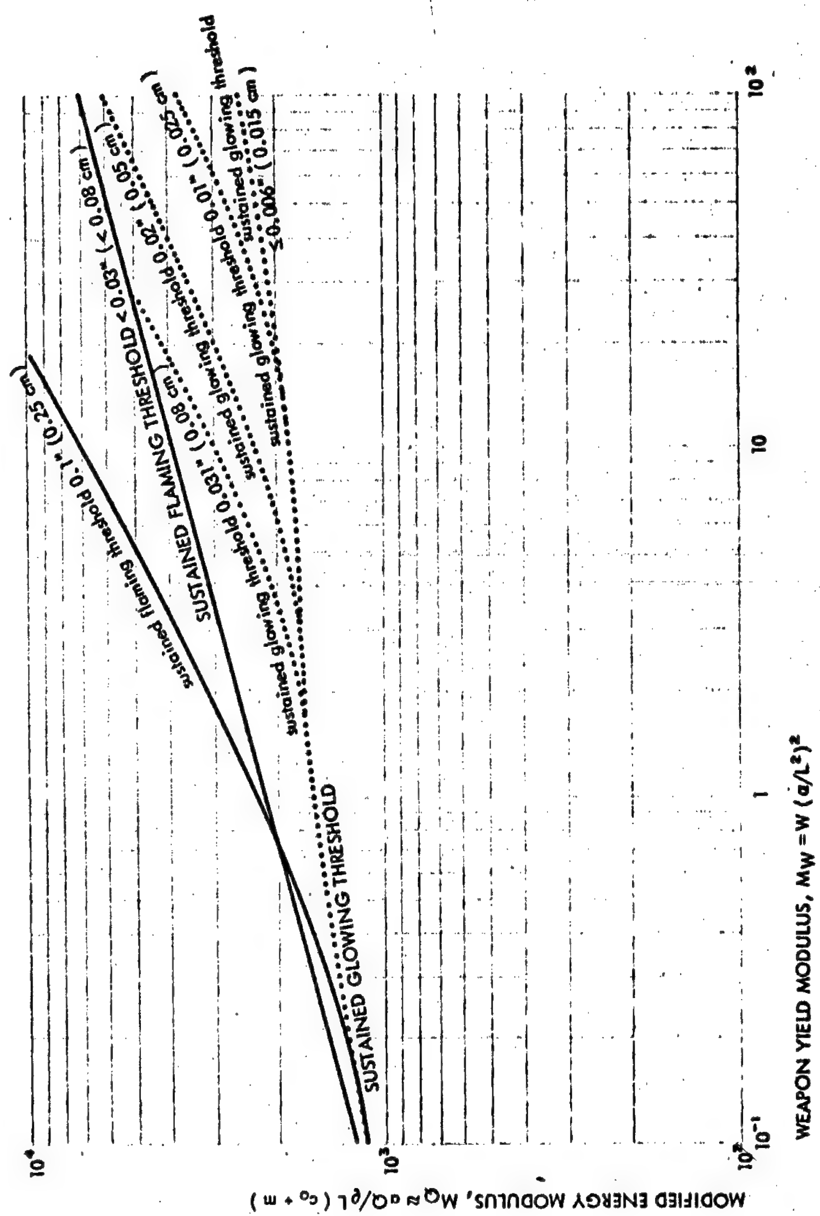
GENERALIZED IGNITION BEHAVIOR, $10^{-4} \leq M_W \leq 10^{-1}$



SOURCE: Martin (1959)

Figure B-30

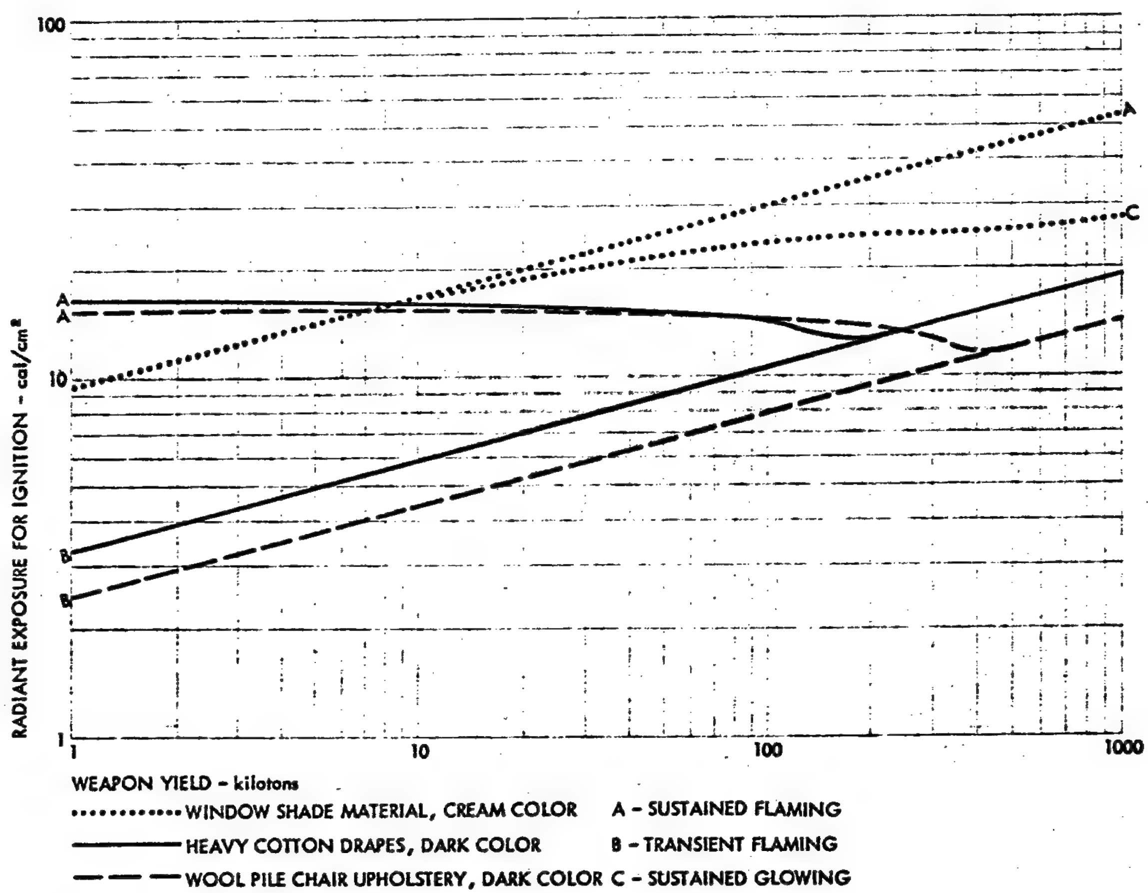
GENERALIZED IGNITION BEHAVIOR, $0.1 \leq M_W \leq 100$



SOURCE: *Martin* (1959)

Figure B-31

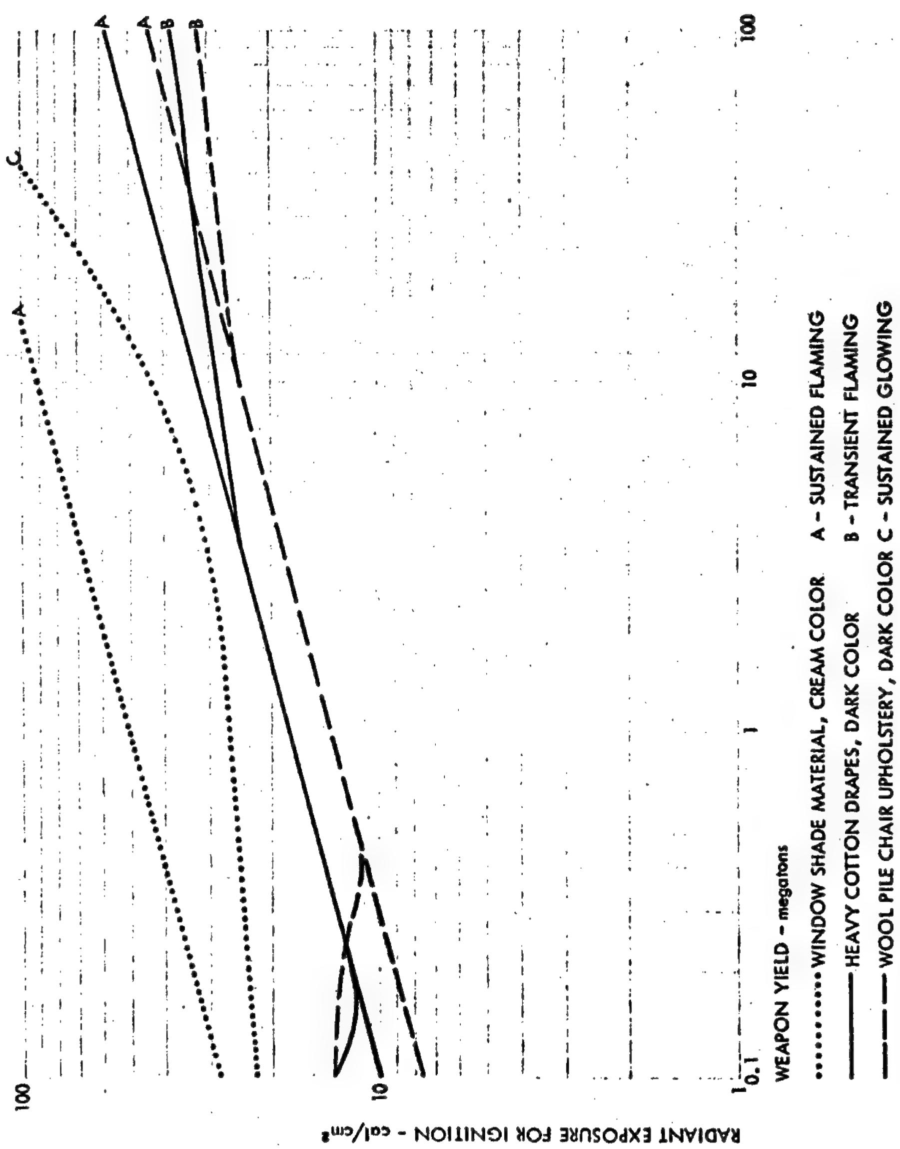
IGNITION THRESHOLDS OF TYPICAL HOUSEHOLD MATERIALS, KILOTON WEAPONS



SOURCE: Martin (1959)

Figure B-32

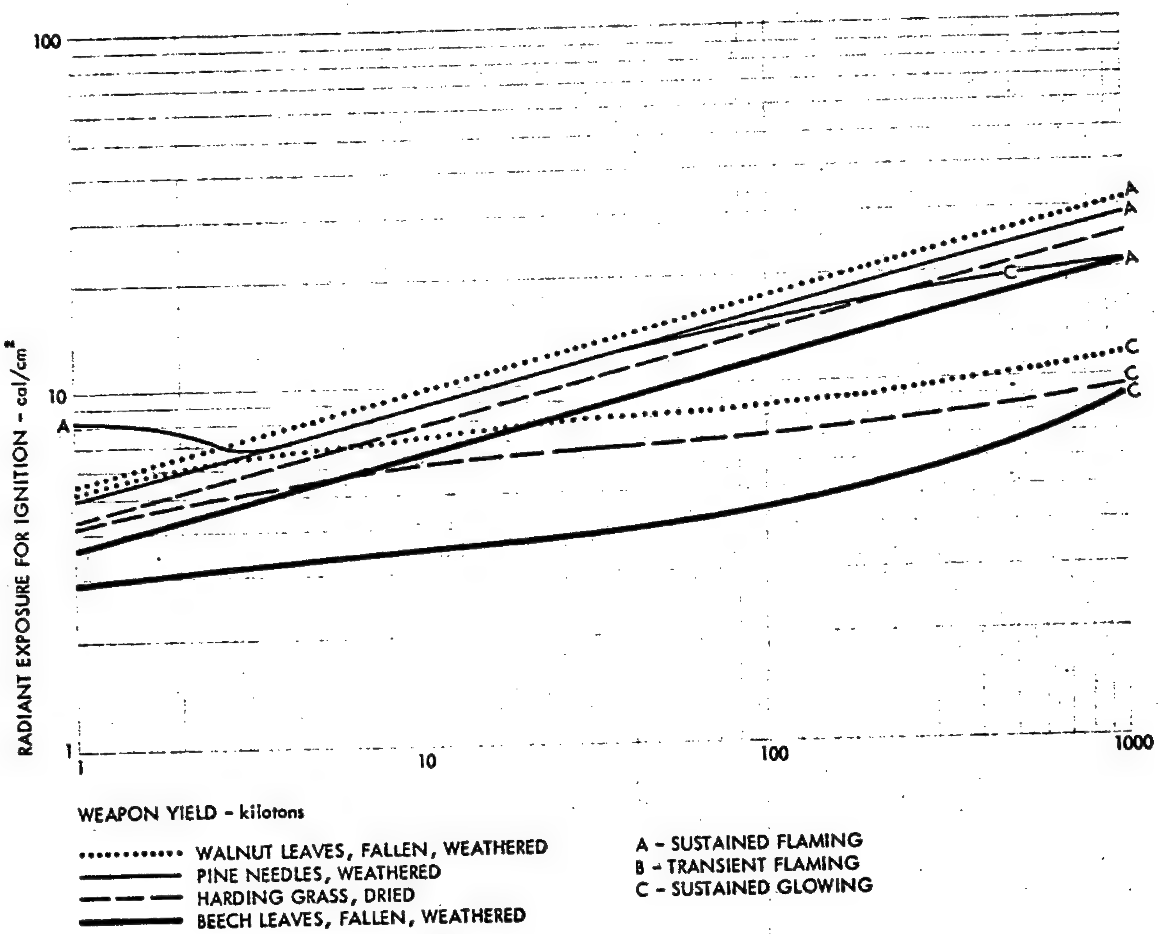
IGNITION THRESHOLDS OF TYPICAL HOUSEHOLD MATERIALS, MEGATON WEAPONS



SOURCE: Martin (1959)

Figure B-33

IGNITION THRESHOLDS OF NATURAL EXTERIOR FUELS, KILOTON WEAPONS

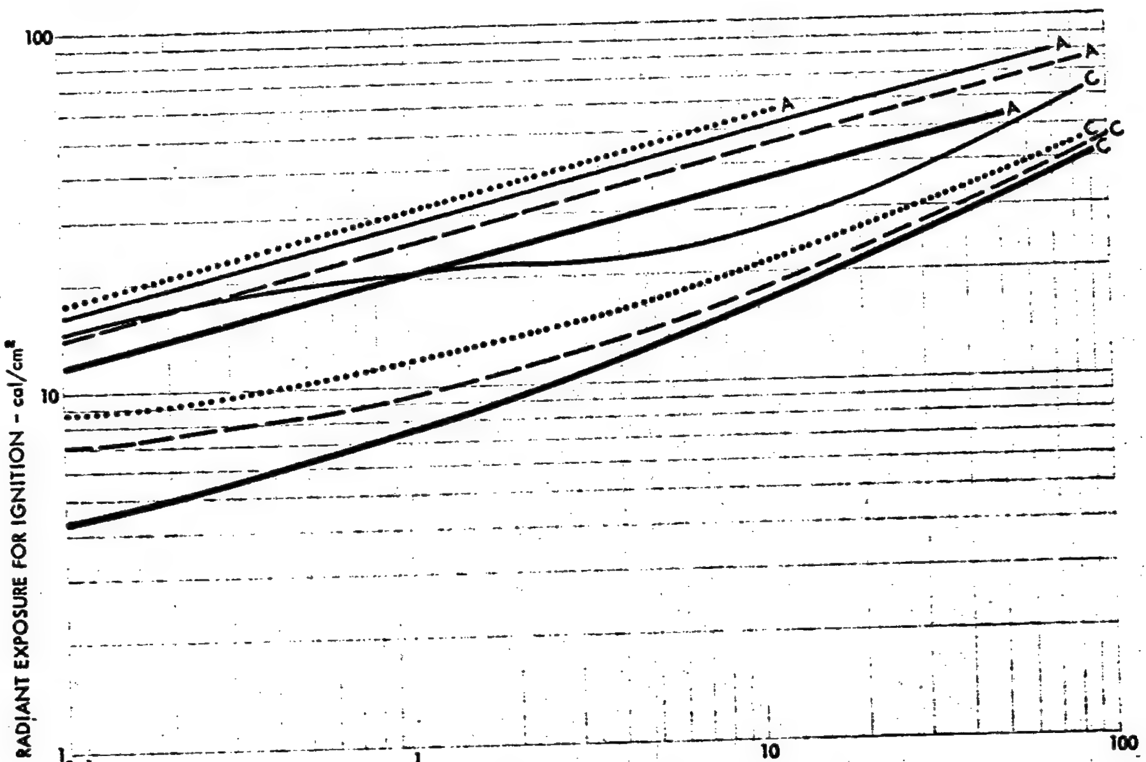


NOTE: Nominal Moisture Content; See Table 10

SOURCE: Martin (1959)

Figure B-34

IGNITION THRESHOLDS OF NATURAL EXTERIOR FUELS, MEGATON WEAPONS



WEAPON YIELD - megatons

•••••••••• WALNUT LEAVES, FALLEN, WEATHERED
———— PINE NEEDLES, WEATHERED
— — — HARDING GRASS, DRIED
▬▬▬ BEECH LEAVES, FALLEN, WEATHERED

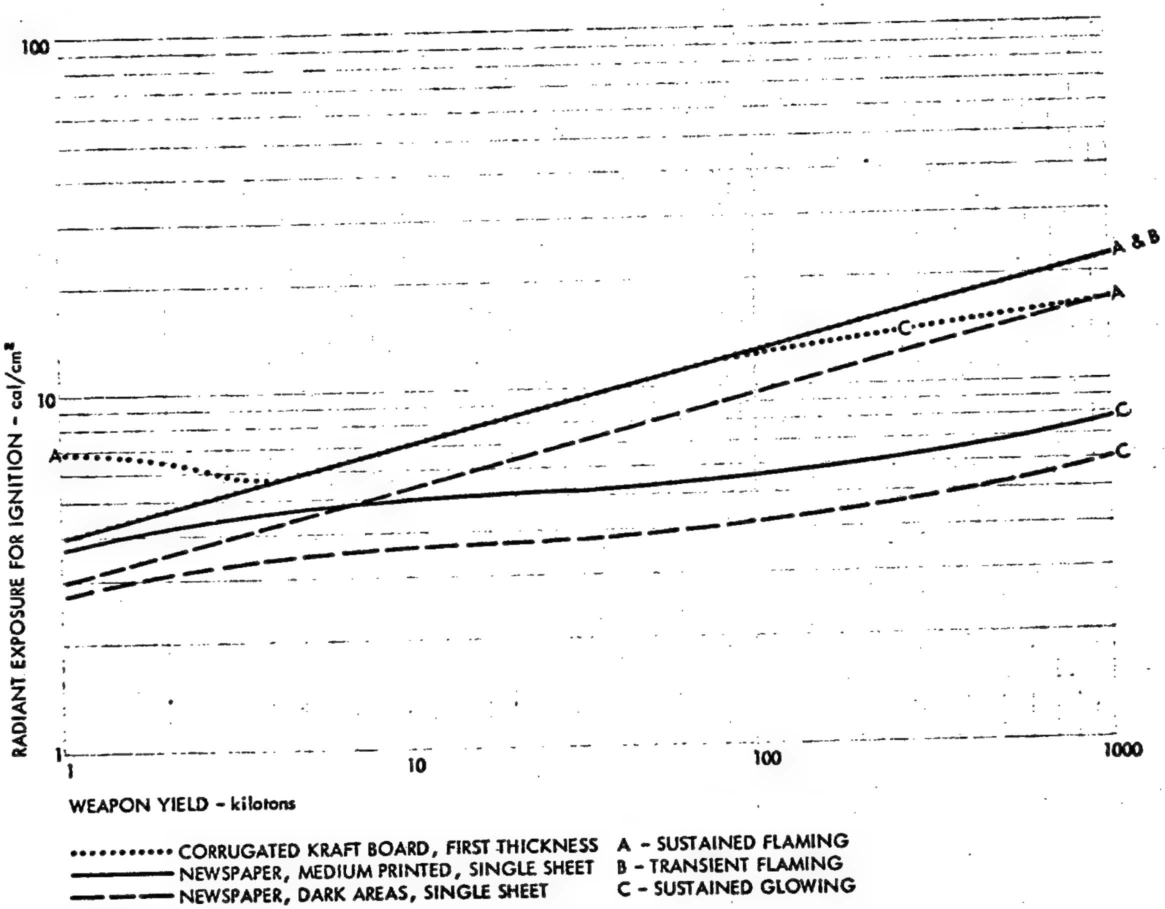
A - SUSTAINED FLAMING
B - TRANSIENT FLAMING
C - SUSTAINED GLOWING

NOTE: Nominal Moisture Content; See Table 10

SOURCE: Martin (1959)

Figure B-35

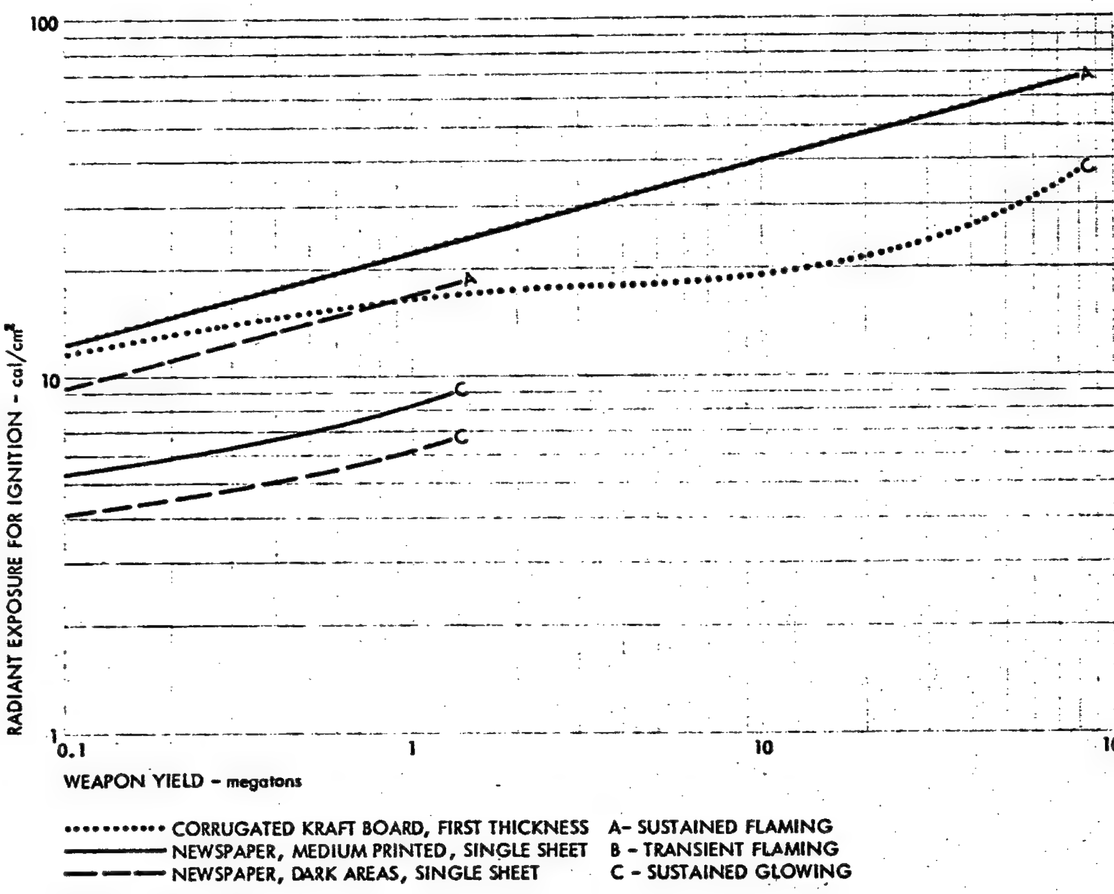
IGNITION THRESHOLDS OF MANUFACTURED EXTERIOR FUELS, KILOTON WEAPONS



SOURCE: Martin (1959)

Figure B-36

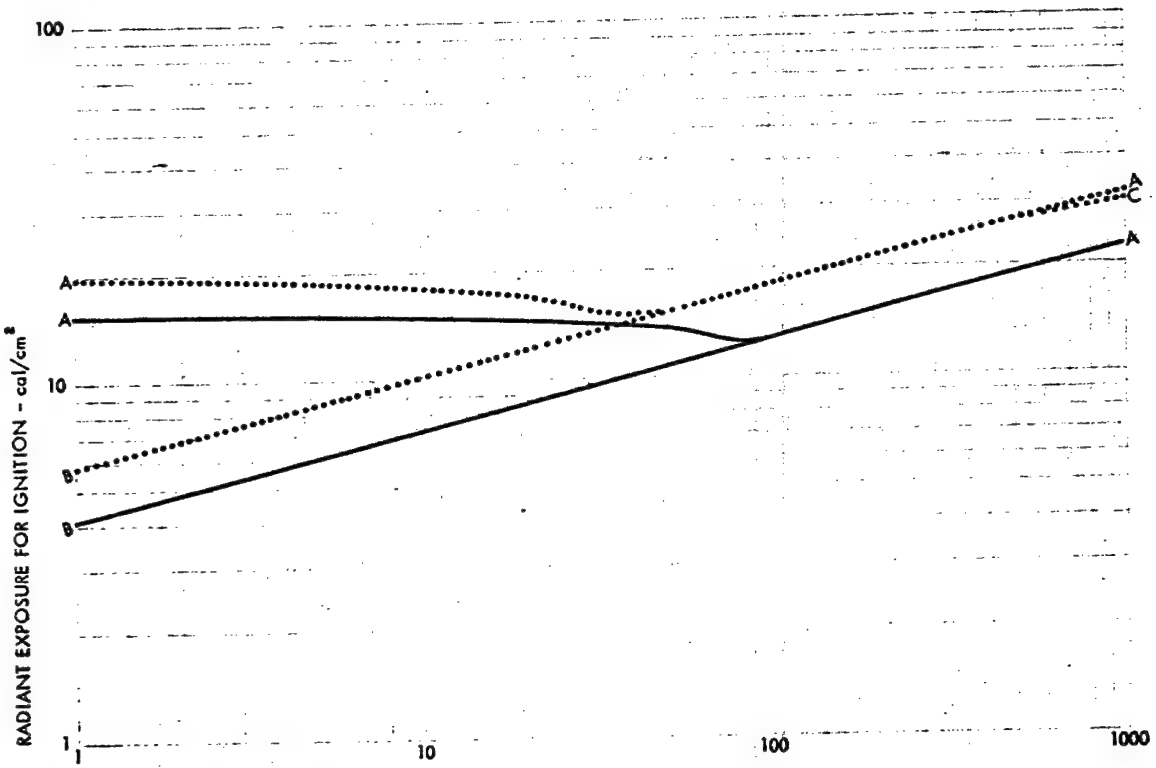
IGNITION THRESHOLDS OF MANUFACTURED EXTERIOR FUELS, MEGATON WEAPONS



SOURCE: Martin (1959)

Figure B-37

IGNITION THRESHOLDS OF MILITARY FABRICS, KILOTON WEAPONS



WEAPON YIELD - kilotons

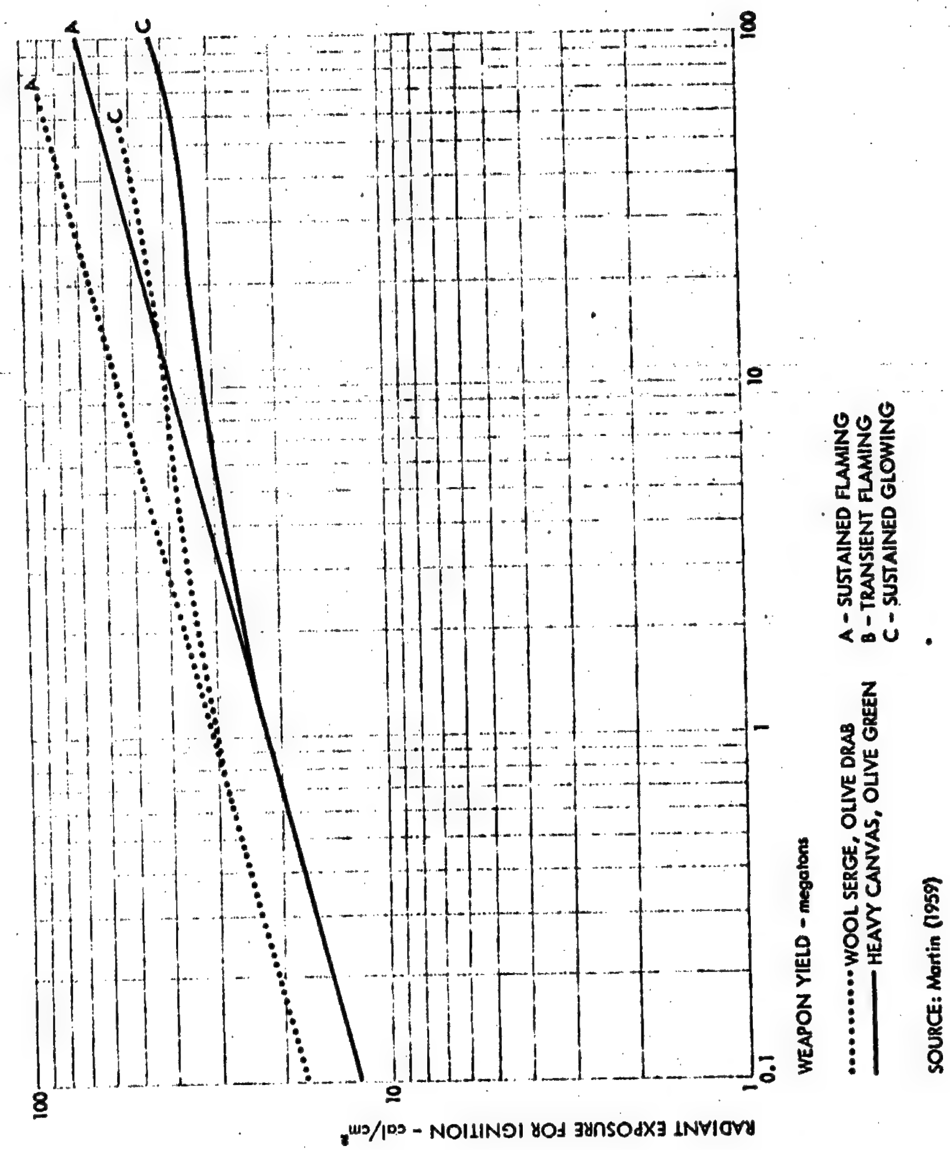
•••••••••• WOOL SERGE, OLIVE DRAB
———— HEAVY CANVAS, OLIVE GREEN

A - SUSTAINED FLAMING
B - TRANSIENT FLAMING
C - SUSTAINED GLOWING

SOURCE: Martin (1959)

Figure B-38

IGNITION THRESHOLDS OF MILITARY FABRICS, MEGATON WEAPONS



3. Considering only the sustained flaming threshold, the curves in Figures B-29 and B-30 can be approximated by two straight lines intersecting at a yield about 1.5 W_e, where W_e is the same as in paragraph 2 above. This is shown in Figures B-39 and B-40. The slopes of the approximating lines are -0.04 and +0.25. Hence, the results for a given material are:

$$Q \sim W^{-0.04} \cong \text{a constant} \quad , \; W \leqslant W_e \qquad (25)$$

$$Q \sim W^{1/4} \quad , \; W \geqslant W_e \qquad (26)$$

In other words, if the calories/cm^2 required for sustained flaming at a given yield are known, the requirements for a different yield may be determined.

4. These results have not been tested for extremely short weapon pulses of less than 0.1 second.* It appears that transient flaming would occur unless the intensity of the pulse were extremely great. (See Figures B-29 and B-30.) In the cases of transient flaming, the surface layer of the material immediately transforms to inflammable gases and explodes. The material beneath this layer is virtually unharmed.

5. The NRDL data apply only to cellulosic materials with very little mineral content. The presence of even a small percentage of mineral content in the fuel will considerably increase its susceptibility to glowing ignition. For the larger yields where glowing ignition would be the usual effect, the ignition energy may be reduced by a factor of 2 or 3 because of mineral content.

6. Based on data in Glasstone (1962), Miller (1962) has concluded that

$$Q \sim W^{0.1} \quad , \quad W = 1 \text{ to } 5.2 \times 10^3 \text{ kt}$$

$$Q \sim W^{0.2} \quad , \quad W > 5.2 \times 10^3 \text{ kt} .$$

The differences between these equations and equations (25) and (26) may be due to the difference in material response as presented in Glasstone and those achieved in the laboratory at NRDL. In general, the calorie requirements for ignition by large yield weapons are much lower in Glasstone than those derived by NRDL. A comparison of these data is shown in Table B-VII for a 10-mt burst. It is difficult to identify the

* See footnote on page 17.

Table B-VII

COMPARISON OF ESTIMATES FOR IGNITION ENERGY REQUIREMENTS
(10 mt)

The Effects of Nuclear Weapons		Naval Radiological Defense Laboratory		
Material	Cal/cm^2 for Ignition	Material	Cal/cm^2 for Ignition	Ratio of NRDL to ENW
Cotton auto seat upholstery, green, brown, white	16	Heavy cotton draperies, dark color	28	1.75
Wool pile chair upholstery, wine	35 (not sustained)	Wool pile chair upholstery, dark color	25	0.7
Newspaper, single sheet	6	Newspaper, medium printed	40	6.7
		Newspaper, dark areas	30	5.
Kraft paper carton, flat side exposed, used, brown	15	Corrugated Kraft board	40	2.6
Deciduous leaves	12	Walnut leaves	54	4.5
		Beech leaves	36	3.
Coarse grass	16	Harding grass	44	2.7
Ponderosa pine needles, brown	18	Pine needles	50	2.7

Sources: Martin, et al. (1959) and Glasstone (1962).

Figure B-39

LINEAR APPROXIMATIONS TO GENERALIZED IGNITION BEHAVIOR, $10^{-4} \leq M_W \leq 10^{-1}$

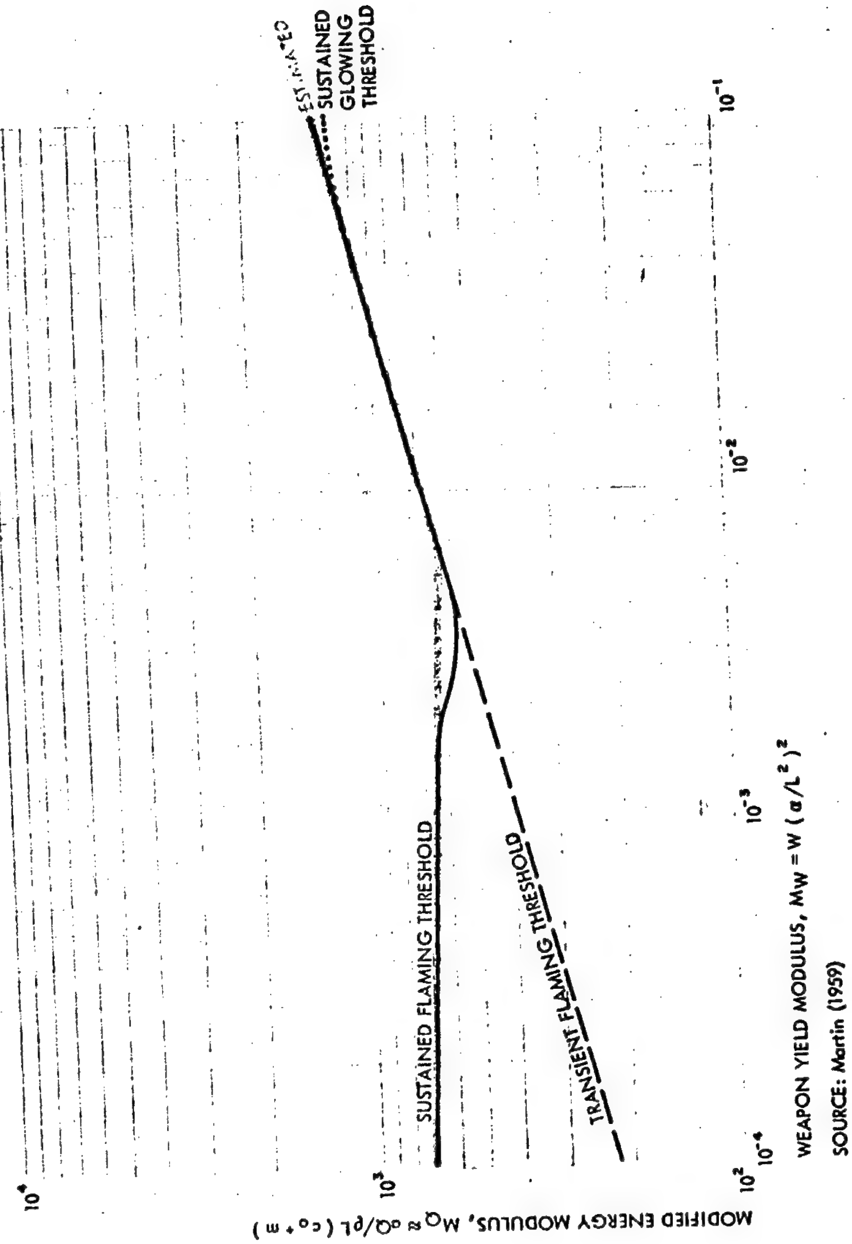
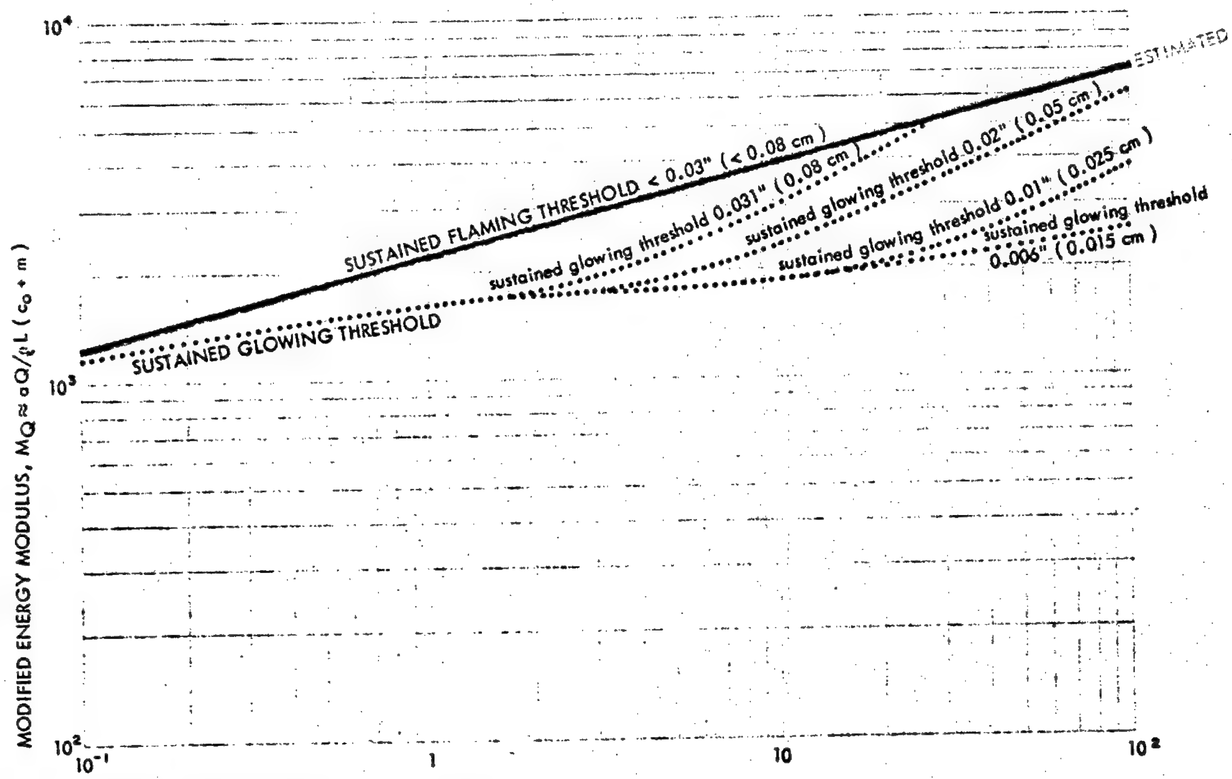


Figure B-40

LINEAR APPROXIMATIONS TO GENERALIZED IGNITION BEHAVIOR, $0.1 \leq M_W \leq 100$



WEAPON YIELD MODULUS, $M_W = W\,(\alpha/L^2)^2$

SOURCE: Martin (1959)

reasons for these differences since Glasstone does not give a source for the data presented. Presumably the data are derived from Upshot-Knothole weapons tests and tests made at the Forest Products Laboratory of the U.S. Forest Service. The data are sufficiently different from the NRDL results that the difference cannot be ignored. It is recommended that the NRDL data be used in preference to that presented in Glasstone. No further research on the effects of thermal pulses on materials is contemplated at NRDL.

To relate the ignition of materials to range, NRDL has used the transmittance data given in The Effects of Nuclear Weapons for an extremely clear atmosphere. These data are shown in Figures B-41 and B-42, and equation (6) leads to Figures B-43 through B-52.

In Figure B-42, it can be seen that the radiant exposure as a function of range is not critically dependent on visibility. If a constant visibility and a corresponding average transmittance (i.e., that T is independent of R) are assumed, equation (6) may be combined with the approximations (25) and (26) to find that the range for ignition varies with yield as follows:

$$R \sim W^{0.5} \qquad W < W_e \tag{27}$$

$$R \sim W^{0.37} \qquad W > W_e \tag{28}$$

where W_e is defined by equation (24). Of course, it is understood that the range, R, is the slant range from the weapon and that the orientation of the material to the weapon remains constant. Figures B-43 through B-52 verify the approximations given in equations (27) and (28). They are only valid, however, under the assumptions that the scaling for weapon effects and transmittance as given in The Effect of Nuclear Weapons are valid. For large yield weapons, the criterion that the slant range is less than half the visibility will probably make the assumptions on transmittance invalid.

Modification of the Thermal Pulse by Materials. Up to this point, only the effect of a high intensity thermal pulse on materials has been considered. As a contrasting effect, materials can be considered to modify the thermal pulse in that they intercede between the energy and other possible targets. Examples of this screening effect are clothing, window glass in structures, venetian blinds, screens, and the like.

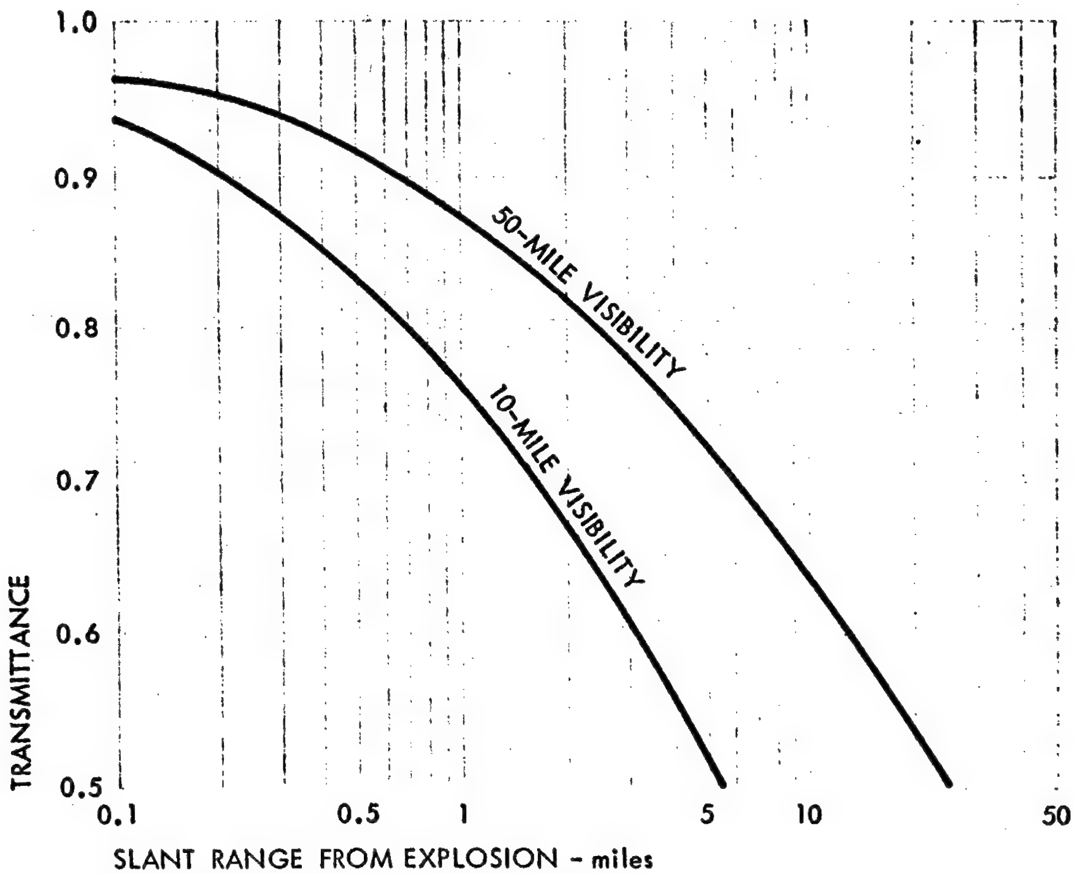
The percent of the energy transmitted through fabrics from a high intensity thermal pulse has been studied at the Naval Material Laboratory; see The Thermal Data Handbook (1954). For example, cotton twill (both with and without a flame retardant treatment), heat-treated orlon, and metalized fabrics have been considered. Although there is some evidence of a reduction in apparent transmittance as a result of flame retardant treatment of white cotton twill, the effect on colored twill may be to increase slightly the apparent transmittance.

Orlon which has been maintained at 250°C for 3-1/2 hours under carefully controlled conditions becomes very resistant to damage from thermal radiation. Untreated orlon is destroyed by 30 cal/cm^2 at a maximum irradiance of 85 cal/cm^2/sec. With the same irradiance, treated orlon requires a destruction energy of 180 cal/cm^2 if the pulse duration is 131 seconds. For shorter or longer pulse durations, the energy required to destroy the treated orlon is much greater: 740 cal/cm^2 for 650 second duration; 5,500 cal/cm^2 for 63 second duration. The transmittance is about 1/2 to 2/3 that of olive drab wool serge (6 percent). Metalized rayon was less resistant to thermal damage than untreated rayon; however, the apparent transmittance of thermal energy was reduced significantly.

The effect of screening of thermal radiation by clothing is complicated by the air space between the clothing and the skin, by underclothing, by perspiration, and so on. Some of the results of tests made

Figure B-41

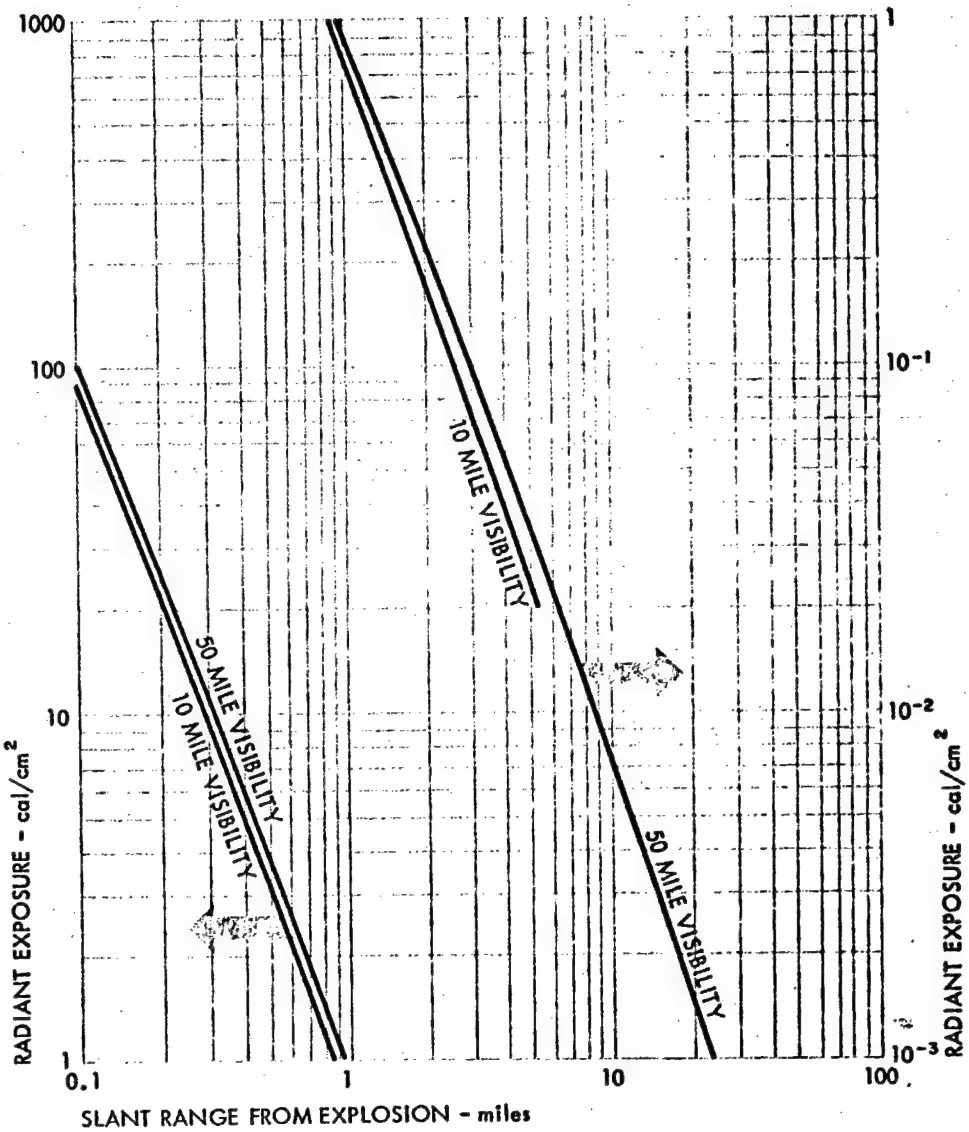
ATMOSPHERIC TRANSMISSION AS A FUNCTION OF DISTANCE FOR VISIBILITIES OF 10 MILES AND 50 MILES



SOURCE: Glasstone (1962)

Figure B-42

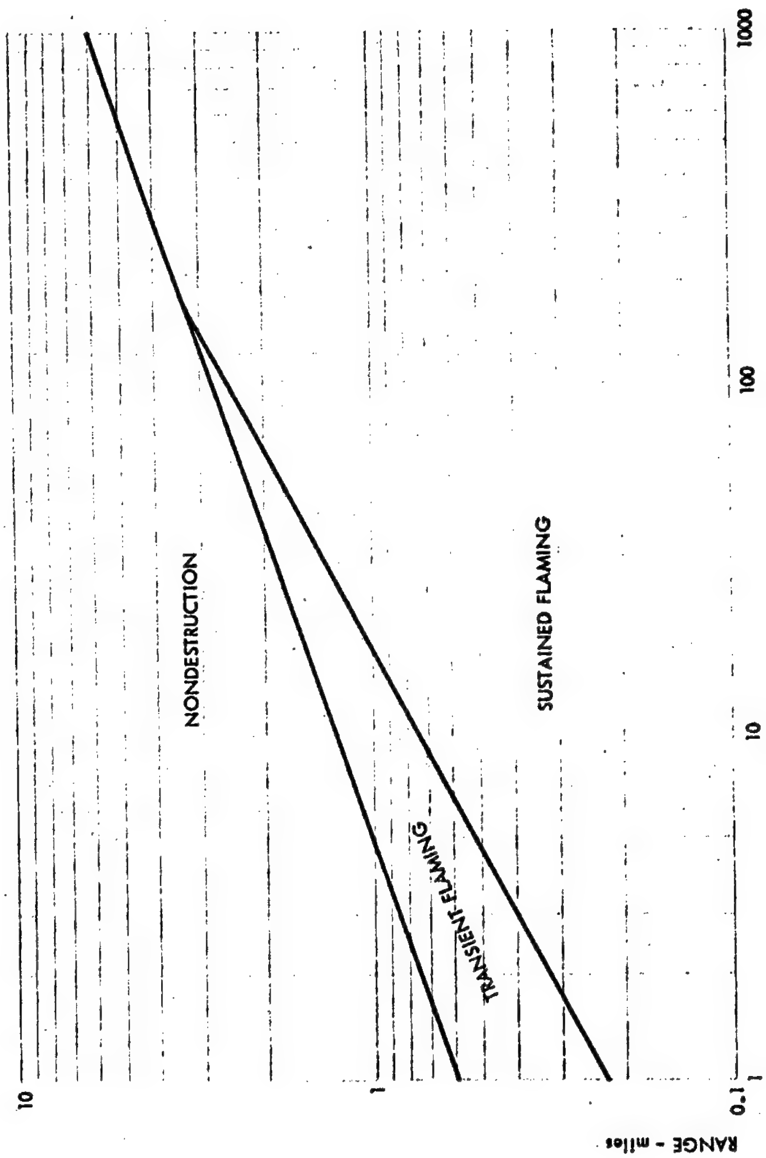
RADIANT EXPOSURE AS A FUNCTION OF SLANT RANGE FROM A 1 KILOTON AIR BURST FOR VISIBILITIES OF 10 MILES AND 50 MILES



SOURCE: Glasstone (1962)

Figure B-43

IGNITION RANGE FOR HEAVY COTTON DRAPERY (DARK COLOR), KILOTON WEAPONS

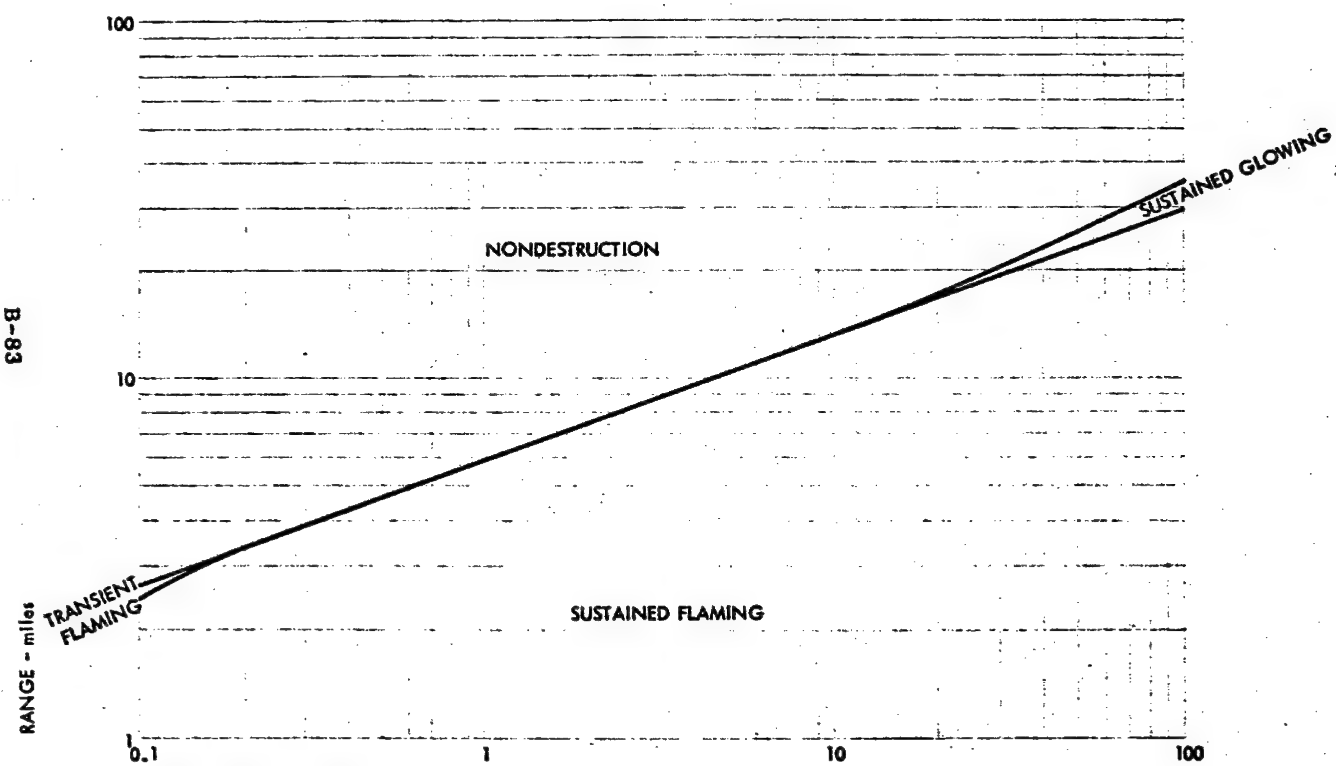


WEAPON YIELD - kilotons

SOURCE: Martin (1959)

Figure B-44

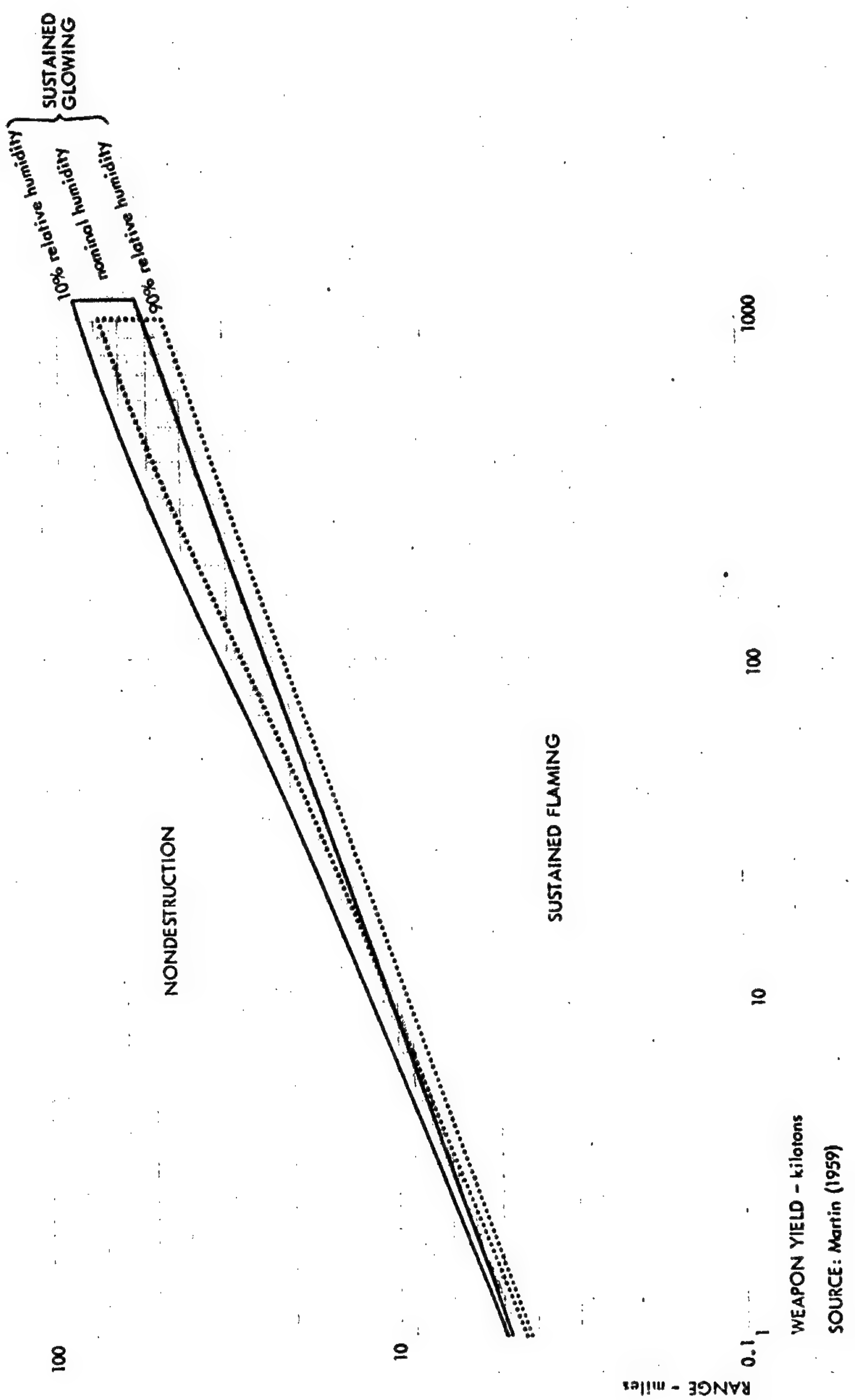
IGNITION RANGE FOR HEAVY COTTON DRAPERY (DARK COLOR), MEGATON WEAPONS



SOURCE: Martin (1959)

Figure B-45

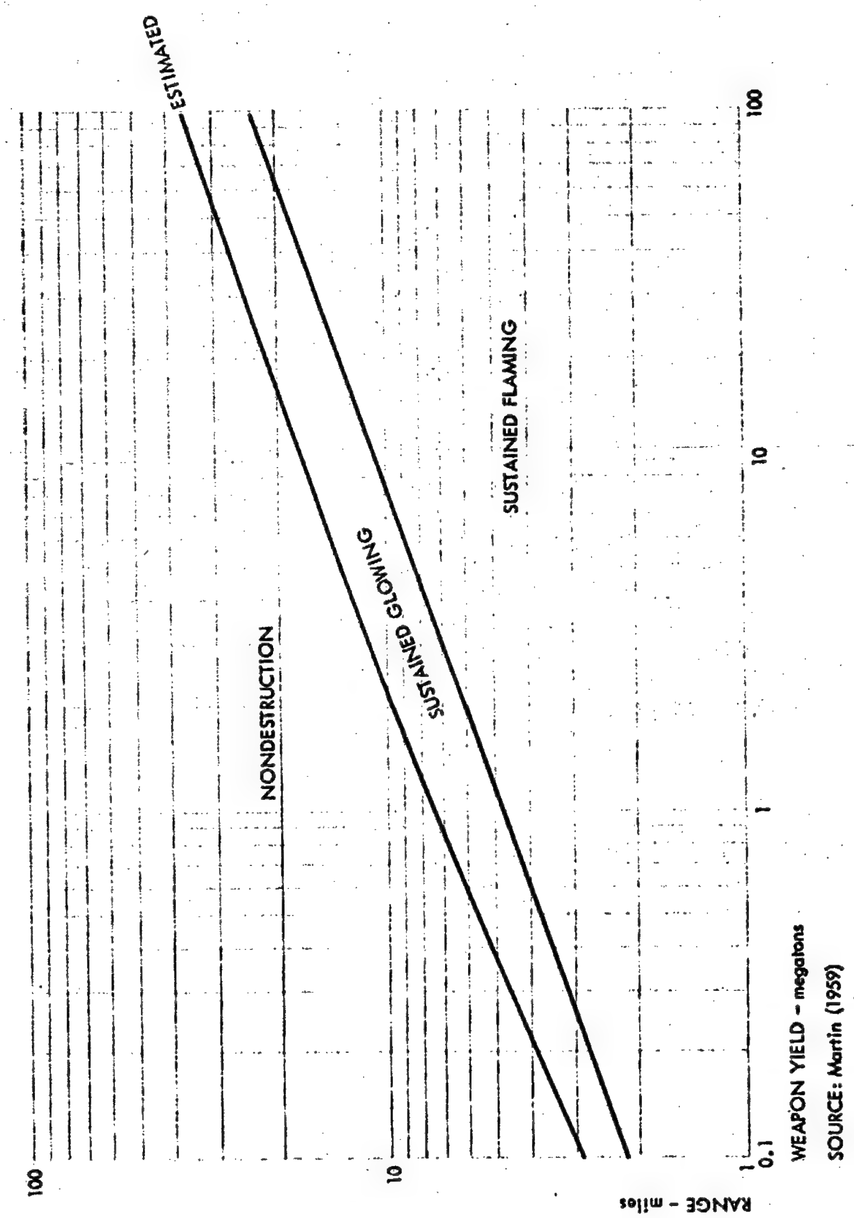
IGNITION RANGE FOR WALNUT LEAVES (FALLEN, WEATHERED), KILOTON WEAPONS



SOURCE: Martin (1959)

Figure B-46

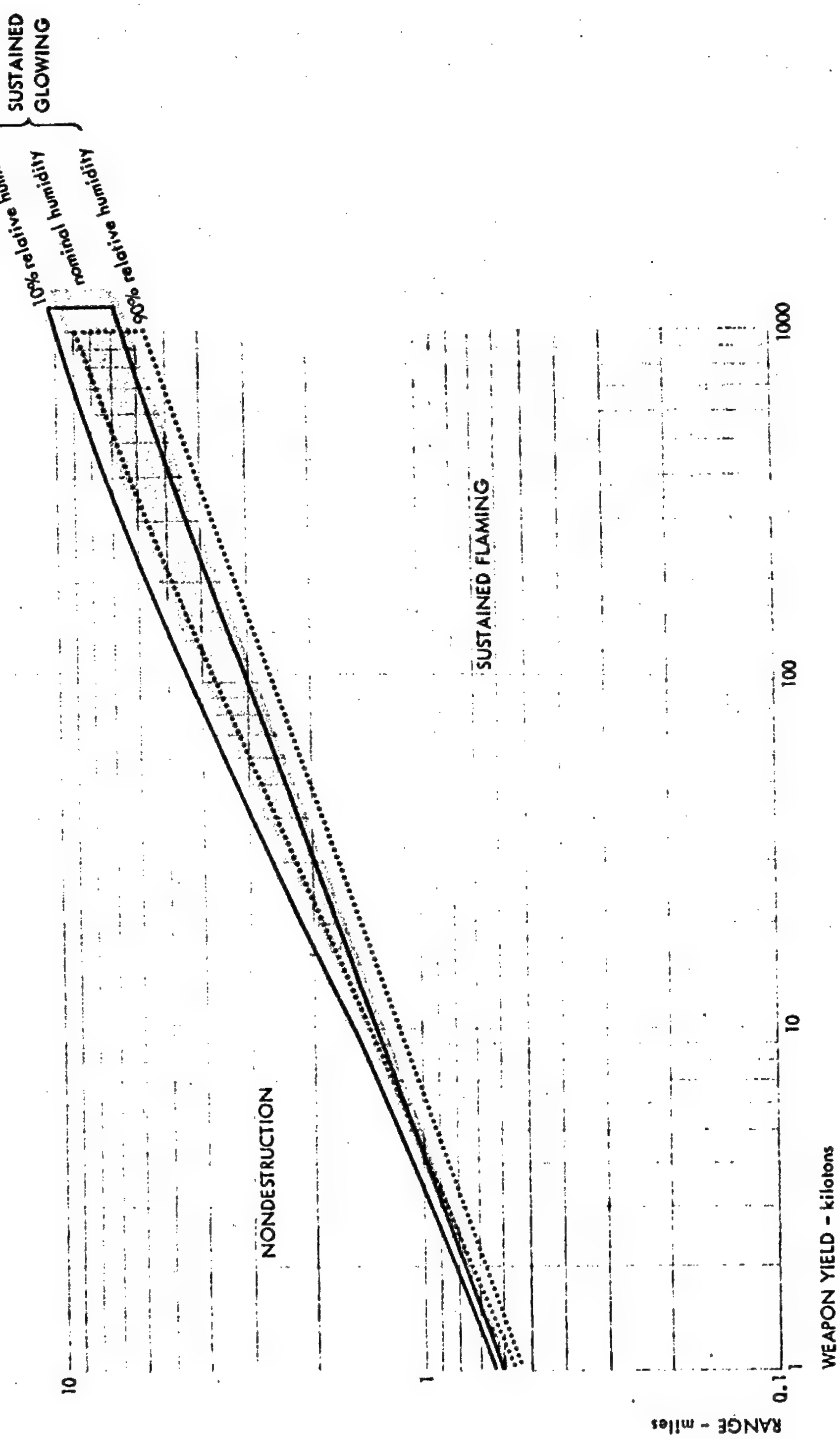
IGNITION RANGE FOR WALNUT LEAVES (FALLEN, WEATHERED), MEGATON WEAPONS



SOURCE: Martin (1959)

Figure B-47

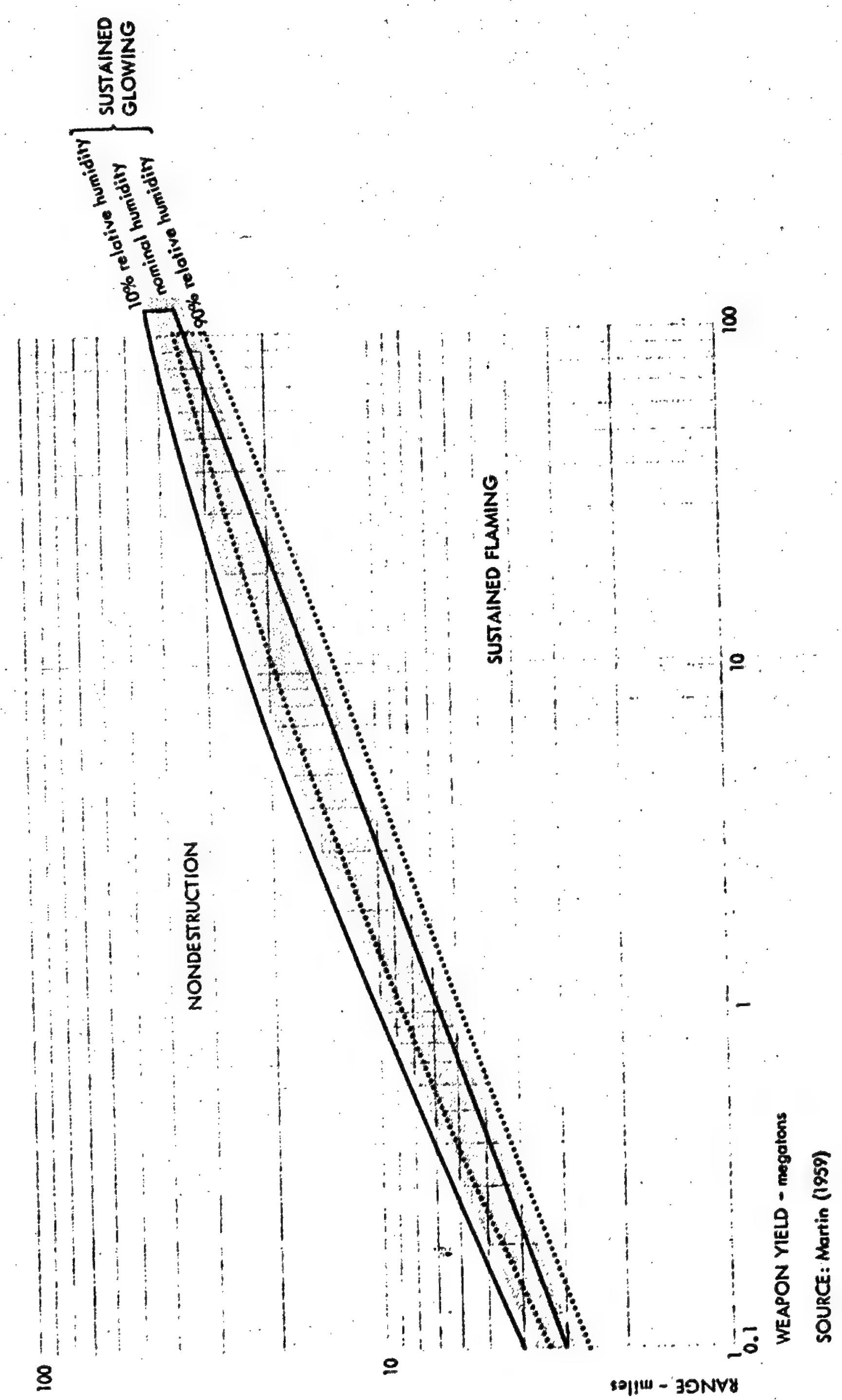
IGNITION RANGE FOR NEWSPAPERS, KILOTON WEAPONS



SOURCE: Martin (1959)

Figure B-48

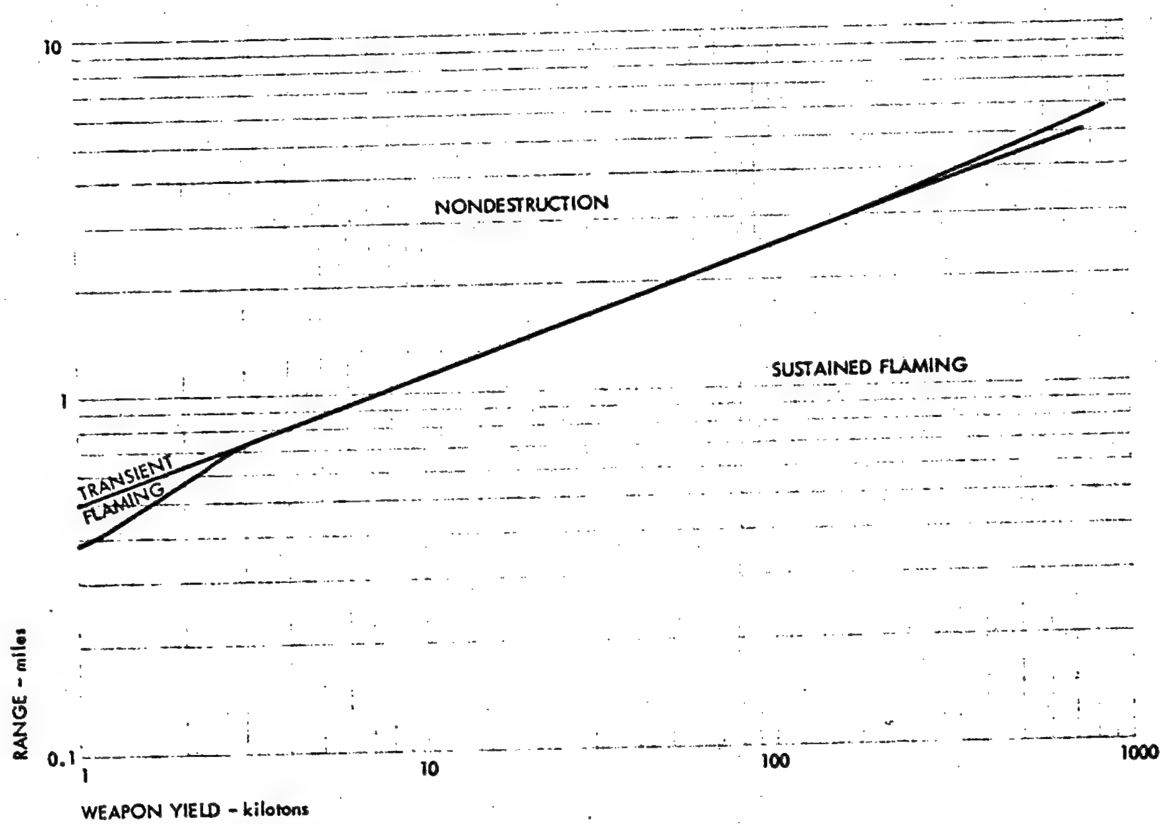
IGNITION RANGE FOR NEWSPAPERS, MEGATON WEAPONS



SOURCE: Martin (1959)

Figure B-49

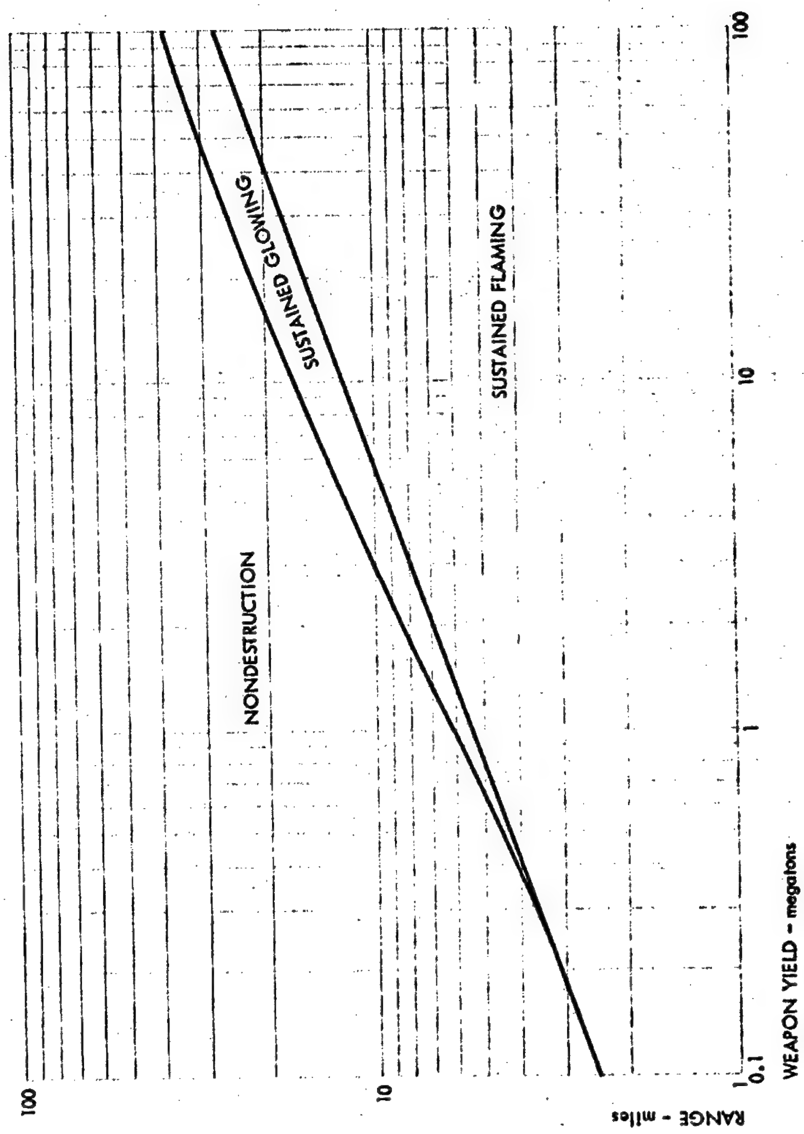
IGNITION RANGE FOR CORRUGATED KRAFT BOARD, KILOTON WEAPONS



SOURCE: Martin (1959)

Figure B-50

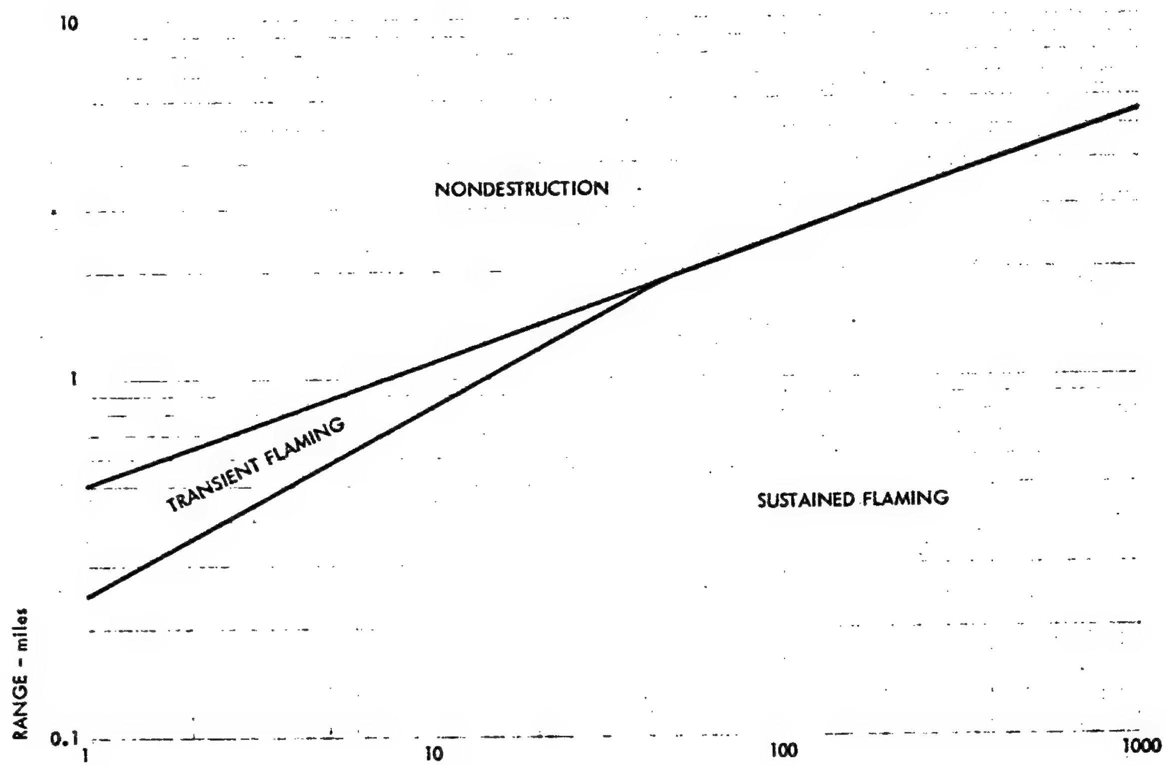
IGNITION RANGE FOR CORRUGATED KRAFT BOARD, MEGATON WEAPONS



SOURCE: Martin (1959)

Figure B-51

IGNITION RANGE FOR HEAVY MILITARY CANVAS, KILOTON WEAPONS

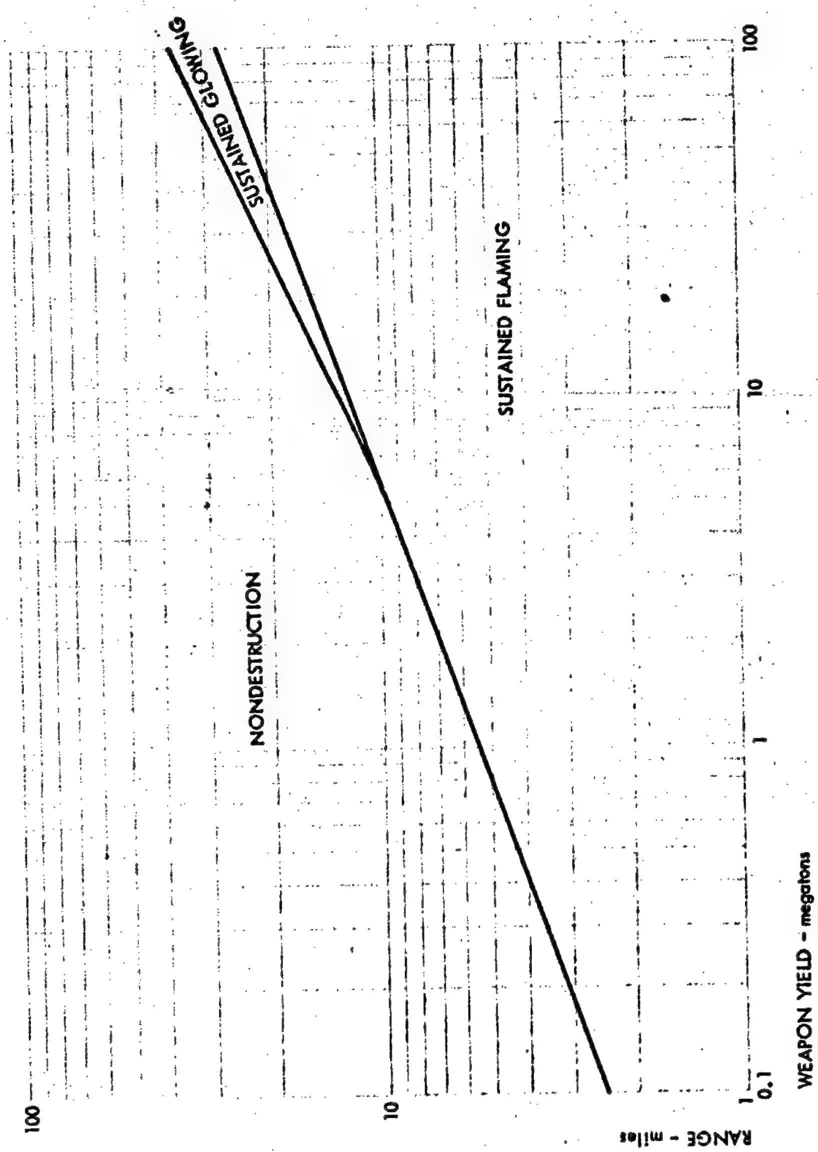


WEAPON YIELD - kilotons

SOURCE: Martin (1959)

Figure B-52

IGNITION RANGE FOR HEAVY MILITARY CANVAS, MEGATON WEAPONS



SOURCE: Martin (1959)

on pigs (second degree burns) are shown in Figure B-53. Additional test results on the skin simulant developed at the Naval Material Laboratory are shown in Figure B-54.

The protection from thermal radiation afforded by window glass has been investigated by Downs and Bruce (1955). Critical ignition energies of 22 materials were measured in the laboratory by exposure to the radiation of a graphite plate at 4200°F, with and without a filter of single strength window glass. To barely ignite a material, the energy per unit area reaching the glass had to average almost twice the energy reaching the material directly. Limited field tests were also made using radiation from a British nuclear weapon of unspecified yield. It appeared here that the window glass offered appreciable protection by absorbing and reflecting about 28 percent of the broad spectrum of the radiation from the fireball. Additional results are presented by Bruce and Downs (1956).*

Field tests were also made by Downs and Bruce (1957) for the protection afforded by window screening. Three typical window screens were found to exclude 31.6, 34.8, and 46.7 percent of the incident light. Commercially available window screens, made from flat metal ribbons rather than wires, gave complete protection, provided the elevation angle of the fireball was greater than about 38° (see Appendix E). Other tests of window screening have been made by Banet and Hirschman (1956).

Effects of the Thermal Pulse on Humans and Animals. The scope of this report precludes an extensive review of research on the effects of the thermal pulse on humans and animals. Nevertheless, the effects are of such a serious nature, would cover such extensive areas, and are in many ways so closely related to the fire threat that they will be given some attention here although no attempt will be made for completeness.

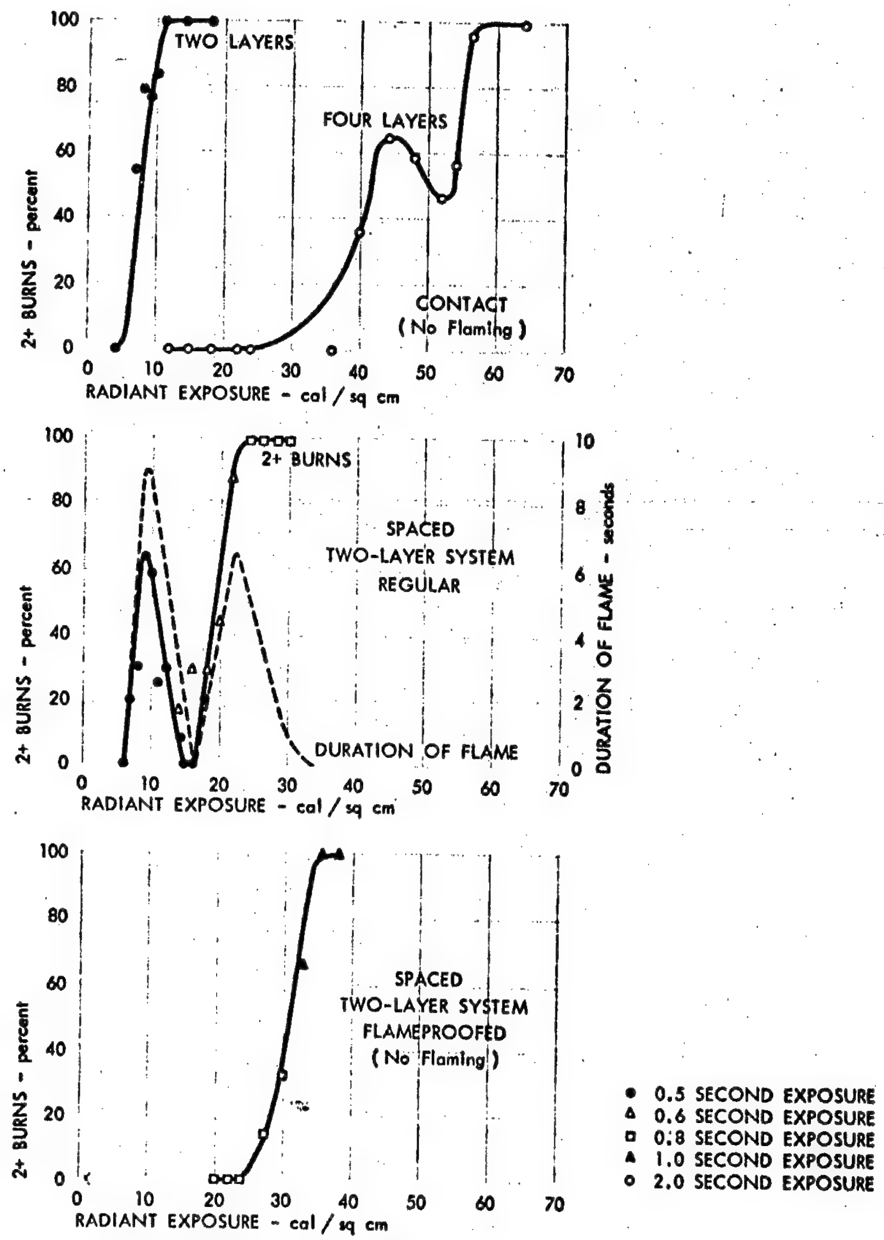
The quantitative information available on the vulnerability of animals and humans to thermal pulses from nuclear detonations has been derived from weapons tests, theoretical calculations, and laboratory studies. In this research, the reactions of pigs, rats, rabbits, and humans, as well as human skin simulants, have been analyzed. It should be pointed out that the tests on animals have been made only to better understand the reactions of humans. No studies have been made of the response of livestock and domestic animals other than pigs and rabbits.

There are four types of damages which may be suffered by humans or animals exposed to a thermal flash. These are flash burns on the skin, retinal burns, temporary flash blindness, and keratitis (an inflamation of the cornea). These will be considered in order.

* See Table B-XX.

Figure B-53

FLASH BURNS OF SKIN:
PROTECTIVE VALUE OF SERVICE
UNIFORMS



SOURCE: Thermal Data Handbook (1954)

Notes to Figure B-53

Jan. 1, 1955

FLASH BURNS OF SKIN

PROTECTIVE VALUE OF SERVICE UNIFORMS:
LABORATORY STUDIES OF 2, 4, AND 6 LAYER FABRIC COMBINATIONS

Exposures required to produce 2+ burns under fabric ensembles as related to the phenomenon of flaming

An example of the complications encountered in attempting to interpret the results of experiments on burns produced under fabrics is described for three service uniform combinations of practical importance. It was found that the probability of producing 2+ burns under a tropical uniform which is spaced from the skin depends on the duration of flaming over a wide range of radiant exposure. Hence, when the outer layer was flameproofed (HPM), considerably more energy was required to produce burns.

Burns were produced on Chester White pigs with the Rochester carbon arc source comprising a 24 inch carbon arc searchlight with an ellipsoidal mirror focusing on an exposure port 1.7 cm in diameter. Such burns were found to differ from those with unprotected skin; for a given degree of surface damage, the depth of damage appeared to be greater as a consequence of prolongation of the heating period. Between four and twenty-six burns were evaluated for each of the points plotted in the accompanying graphs. The resulting curves show the percent of 2+ burns (corresponding to 2nd degree burns in humans) produced at various exposures to pigs clothed with two layers (tropical uniform) or four layers (temperate uniform) in contact with, and separated from, the skin. Under six layers (arctic uniform) no 2+ burns were produced with exposures up to 108 cal/sq cm. Uniform assemblies were as follows, reading from outside in:

Two layers—Cotton, Oxford, light green; Cotton, knit, underwear

Four layers—Cotton, sateen, OG; Cotton, Oxford; Wool-nylon shirting; Cotton, knit, underwear

Six layers—Cotton, sateen, OG; Cotton, Oxford; Mohair frieze; Rayon lining; Wool-nylon shirting; Wool, knit, underwear.

Contact: The two-layer tropical uniform increased the amount of energy required to cause 50% 2+ burns, EQ_{50}, from 3.5 to 7.5 cal/sq cm, and, hence, may be said to give 4 cal/sq cm protection. Flameproofing did not increase the protection afforded by this system. The four-layer system gave 40 cal/sq cm protection and is, therefore, adequate protection within the region where thermal effects are predominant.

Spaced: The most significant feature of the tests in which the uniform was spaced 5 mm from the skin was the occurrence of persistent flaming. Burns reached a peak, in number and severity, at 10 cal/sq cm but dropped to a minimum when exposures were increased to 15 cal/sq cm. The latter exposure failed to produce even mild 1+ burns.

A second EQ_{50} was found at 20 cal/sq cm and at higher exposures the probability for 2+ burns rapidly attained 100 percent. The first maximum, and the ensuing minimum, were found to correlate closely with the duration of flaming of the outer layer. For instance, the carbon arc exposure of 10 cal/sq cm delivered in 0.5 second was followed by flaming which lasted for nine seconds. An exposure of 15 cal/sq cm, however, so destroyed the outer fabric that flame was not supported; increasing exposure levels then ignited the inner layer.

Spaced, flameproofed: In the absence of flaming of the outer layer, no burns were produced until it had been destroyed. An EQ_{50} of 30 cal/sq cm testifies to the advantages of flameproofing in this system.

SOURCE: *The Thermal Data Handbook* (1954).

Classified Figure B-54 on energy transference has been deleted.

Notes to classified Figure B-54
have been deleted.

In the Effects of Nuclear Weapons, it is stated that 20 to 30 percent of the fatal casualties in Hiroshima and Nagasaki were caused by flash burns. Approximately 90 percent of the Japanese who sought aid within the first week following the atomic bombing did so because of thermal injury; see Sulit (1960). For the weapon yields and environmental conditions prevailing in these two attacks, there is ample evidence to support the seriousness of the flashburn threat. In the following paragraphs, data are presented for burns on bare skin. The effect of clothing and other shielding is considered in this appendix and Appendix E.

By far the bulk of the laboratory work done on flashburns has been undertaken at the University of Rochester, the Naval Material Laboratory, and the Naval Radiological Defense Laboratory. The work done by these and other agencies is summarized in The Thermal Data Handbook (1954), which is a basic source of information in this report.

Two classified paragraphs on burns have been deleted.

The thermal exposures causing burns of moderate severity to Chester White pigs are given in Table B-VIII.

Classified paragraph on burns has been deleted.

Table B-VIII

MEDIAN ENERGY REQUIRED TO PRODUCE BURNS
OF PIG SKIN IN EXPOSURES OF 0.3 SECOND

Cal/sq cm	Type of Burn (moderate)
2.0	1+
3.7	2+
6.3	3+
9.0	4+
21.0	5+

Figure B-55 shows the results of experimental and theoretical studies of the variation of radiant exposure required to produce burns on pigs as a function of the time of exposure to an essentially square thermal pulse. These results are very similar to those produced on rats at NRDL, if an adjustment is made for the triangular shaped pulse used at NRDL.

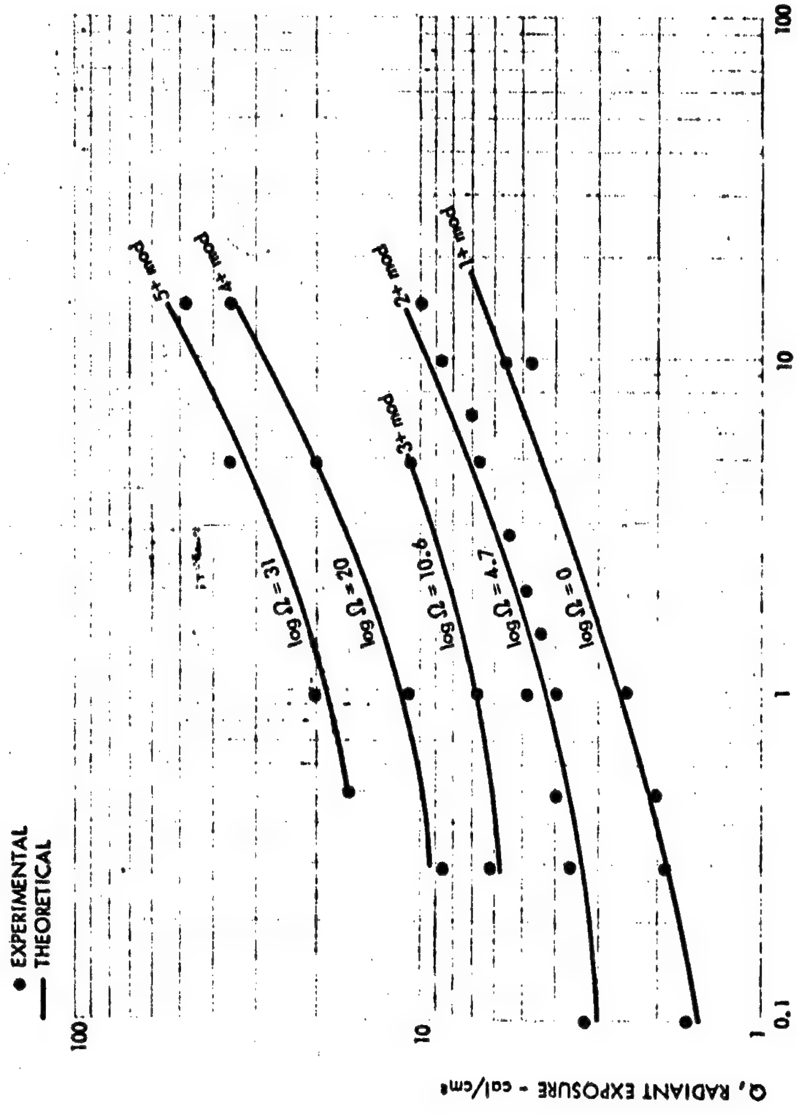
By using the theory resulting in the curves in Figure B-55 and correcting for the shape of the weapon pulse, Figure B-56 was derived--see Thermal Data Handbook (1954)--to show the thermal energy required to cause burns as a function of weapon yield. The plotted points are field-test data from Operations Greenhouse and Snapper, and although they are not necessarily threshold values, they tend to substantiate the curves. Included also (dashed line) are laboratory results on rats exposed to a simulated field pulse.

Because of the possibility that humans may be able to find shelter from the thermal pulse, studies were made of burns resulting from fractions of the pulse from an atomic weapon. The results are most clearly shown in Figure B-57 where the critical burn radius for a 2+ burn has been plotted as a function of weapon yield for no evasion, 3 second response, and 1 second response. Note that the atmosphere is assumed to be very clear in these calculations. Evidently Figure B-42 or a similar graph was used for atmospheric transmittance.

Classified paragraph pertaining
to the critical burns radius
has been deleted.

Figure B-55

EFFECT OF EXPOSURE TIME ON THE ENERGY REQUIRED TO CAUSE SKIN BURNS OF VARIOUS DEGREES OF SEVERITY



SOURCE: Thermal Data Handbook (1954)

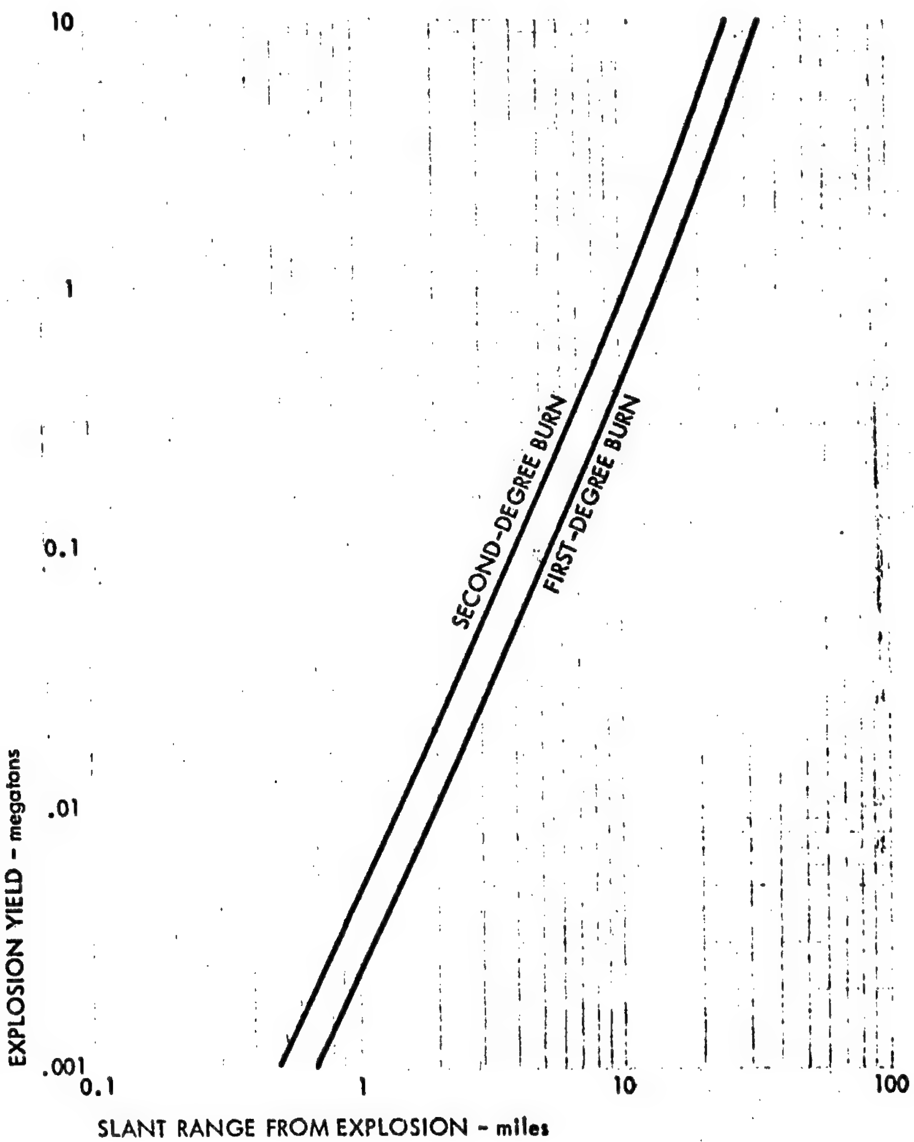
Classified Figure B-56 on energy required to produce burns has been deleted.

Classified Figure B-57 pertaining
to flash burns has been deleted.

Notes to classified Figure B-57
have been deleted.

Figure B-58

RANGES FOR FIRST-AND SECOND DEGREE BURNS AS A FUNCTION OF THE TOTAL ENERGY YIELD



SOURCE: Glasstone (1962)

Additional work on flashburns, skin temperatures, and skin simulants is continuing at the Naval Material Laboratory; see Derksen, et al. (1960).

Damage to the retina of the eye will occur at much greater distances from a nuclear detonation than will most other effects because of the focusing action of the eye. Under the assumptions that the subject is looking in the direction of the fireball and that there is no attenuation of the energy by the atmosphere, the image of the fireball on the retina will become smaller with slant range. However, the energy per unit area which strikes the retina will remain nearly constant since both the total energy and the area of the image are inversely proportional to the square of the slant range from the detonation. Because of chromatic aberration, for very long slant ranges the image on the retina reaches a minimum diameter of about 10 microns (0.001 cm); see Glasstone (1962). Beyond that range the image size remains constant, the energy still varies inversely with the square of the range, and the energy per unit area drops off rapidly.

Additional factors affect the possibility of retinal burns. For one thing, the energy received by the retina is proportional to the opening of the eye. Hence, the response in bright sunlight would be considerably different from that on a cloudy day. Furthermore, the blink response may protect the eye from weapons for which the total thermal energy is distributed over a long period of time--for example, the low altitude, high yield bursts.

Classified paragraph concerning
retinal burns has been deleted.

As was seen in the section concerning the effect of altitude on the thermal pulse shape, the thermal energy from a very high altitude detonation is delivered in a very short time. In the TEAK shot, which occurred at an altitude of 40 miles, the thermal pulse was too weak to cause even minor skin burns at ground zero. Yet, lesions which were approximately 2 millimeters in diameter were caused at about 40 miles; these decreased to 0.5 millimeters at 300 miles; see Broido (1962). As a contrast to this and to show the importance of the atmosphere, the Orange burst, which was also detonated at high altitude, caused no thermal radiation effects because of the cloud cover that existed at detonation time.

Table B-IX gives estimates of the limiting distances for chorioretinal (permanent eye) burns in humans for a 20-kt low air burst. As can be seen, the results are dependent upon the visibility and the pupil opening diameter. The data were derived from tests with rabbits, and the assumption was that in humans an exposure of 0.1 cal/cm^2 for a period of about 0.15 second would produce a minimal eye burn. Work is continuing on the study of retinal burns. Recent experiments have been made, for example, using lasers to simulate the weapon pulse; Rose (1961). It was found that the pigment in the eye can vary its vulnerability considerably.

Table B-IX

ESTIMATED LIMITING DISTANCES FOR CHORIORETINAL BURNS IN HUMANS FOR A 20-KILOTON LOW AIR BURST

	Distance in Miles for Pupil Opening Diameters of:		
Visibility (miles)	2 mm (bright sunlight adapted)	4 mm (cloudy day)	8 mm (completely dark adapted)
25	23	31	40
12	11	16	20
6	6	8	10
2	2	3	4

Source: Glasstone (1962).

Flash blindness is a temporary loss of vision due to receipt by the retina of radiant energy which is too weak to cause a burn but is stronger than necessary for image perception. Some field tests on flash blindness have been made on human subjects at Operation Buster, Snapper, Upshot-Knothole, and Plumbbob; see the Nuclear Radiation Handbook, Wise (1959), and Gulley, et al. (1957).

Classified paragraph on flash blindness has been deleted.

Finally, the eye injury known as keratitis (an inflamation of the cornea) is reported for about 56 persons out of a sample of 1,000 survivors of Hiroshima and Nagasaki. As reported in The Effects of Nuclear Weapons, the symptoms include pain caused by light, foreign-body sensation, lachrymation, and redness. These symptoms may appear immediately or as long as a month or more after the explosion. In no case was permanent injury to the cornea observed, and three years after the detonations all corneas were found to be normal.

Two classified paragraphs pertaining to eye injuries from fireball stimulus have been deleted.

Classified Figure B-59 on blink response and head response has been deleted.

Effects of the Thermal Pulse on Vegetation. The direct effects of the thermal pulse from a nuclear weapon on vegetation are twofold. First, all or part of the vegetation may consist of kindling materials which would be ignited by the flash. The ignition of these materials has been discussed previously in this report. It should be pointed out that no studies have been made which directly relate the parameters identified as important to the response of materials (thickness, density, diffusivity, absorptance, moisture content, or humidity) to the parameters used in computing forest fire indices. The forest fire danger indices, being predominantly an indication of the danger of fire spread, involve parameters such as wind speed, slope of the terrain, days since new growth (for brush fuels), visibility, and so on. The only common factors between the laboratory studies of material response and the forest fire danger indices are the factors of humidity or moisture content and (indirectly) the type and condition of vegetation; see Fireline Notebook (1960), Pirsko (1950), and Davis (1959).

Table B-X gives a description of various classes of forest kindling fuels and Figure B-60 shows their estimated requirement for ignition. To find the minimum radiant exposures for a yield other than 1 kt, multiply the exposures read from the figure by $W^{1/8}$. These results do not apply for weapons in the megaton range.

Table B-X

CLASSES OF THIN WILDLAND KINDLING FUELS
(Arranged in Order of Decreasing Flammability)

Class	Description
I	Broadleaf and coniferous litter--mixture of fine grass, broken leaves and duff, and thin translucent broadleaf leaves
II	Hardwood and softwood punk in various stages of decay
III	Cured or dead grass
IV	Conifer needles and thick, nearly opaque broadleaf leaves

Source: Capabilities of Atomic Weapons (1957).

Classified Figure B-60 on radiant exposure has been deleted.

In an unpublished manuscript, S. Martin, who was responsible for much of the work on the response of materials at NRDL, has made estimates for the material parameters for wildland Classes I, III, and IV shown in Table B-X. He has made use of the parameters

$$X = -\log\left(0.032\sqrt{\kappa/\rho L^2}\right)^2$$

$$Y = 1 + \log\left(a/\rho L\right)^2$$

where $\sqrt{\kappa/L^2}$ and $a/\rho L$ are precisely as shown in Figures B-29 and B-30. Values for the parameters X and Y are shown in Table B-XI. Using these data, a figure similar to Figure B-60 could be derived which would hold for megaton yields.

Table B-XI

IGNITION PARAMETERS FOR WOODLAND CLASSES I, III, AND IV

Class	X	Y
I	0.6 - 2.0	3.0 - 4.0
III	2.0 - 2.5	2.7 - 3.0
IV	2.5 - 3.6	1.3 - 2.7

Source: S. Martin in an unpublished manuscript.

The second effect of a thermal pulse on vegetation is the possible killing of living growth by the intense heat. Some data on killing temperatures of pine needles is given by Davis (1959). Another reference available on this effect is Fons, et al. (1950). In this document theoretical calculations are made of the killing radius to vegetation for a nominal weapon. The following is abstracted:

"It is probable that the lethal effects of thermal radiation on living foliage are of minor importance compared to the ignition effects on dead fuels. Only that part of the tree crown facing the fireball would be affected, and on the exposed side killing would be confined mostly to surface foliage. Near the limiting distance at which lethal effects occur, only those leaves and parts of leaves normal to the direction of radiation would be killed. The initial temperature of the leaf is an important factor in influencing the distance at which the

killing of vegetation will occur. Table III [Table B-XII in this report] shows how the radius of lethal effects for leaves of two different thicknesses varies with initial vegetation temperature. Visual range is given a value of 12 miles. The leaves are assumed to be normal to the radiation and to have moisture content of 200 percent."

Table B-XII

RADIUS OF LETHAL EFFECTS FOR LEAVES

Initial Vegetation Temperature (°C)	Thickness = 0.008 cm		Thickness = 0.032 cm	
	Energy Required (cal/cm^2)	Distance (feet)	Energy Required (cal/cm^2)	Distance (feet)
0	0.66	17,000	2.64	10,200
10	0.55	18,000	2.20	11,000
20	0.44	19,300	1.76	12,000
30	0.33	21,000	1.32	13,300
40	0.22	24,000	0.88	15,400

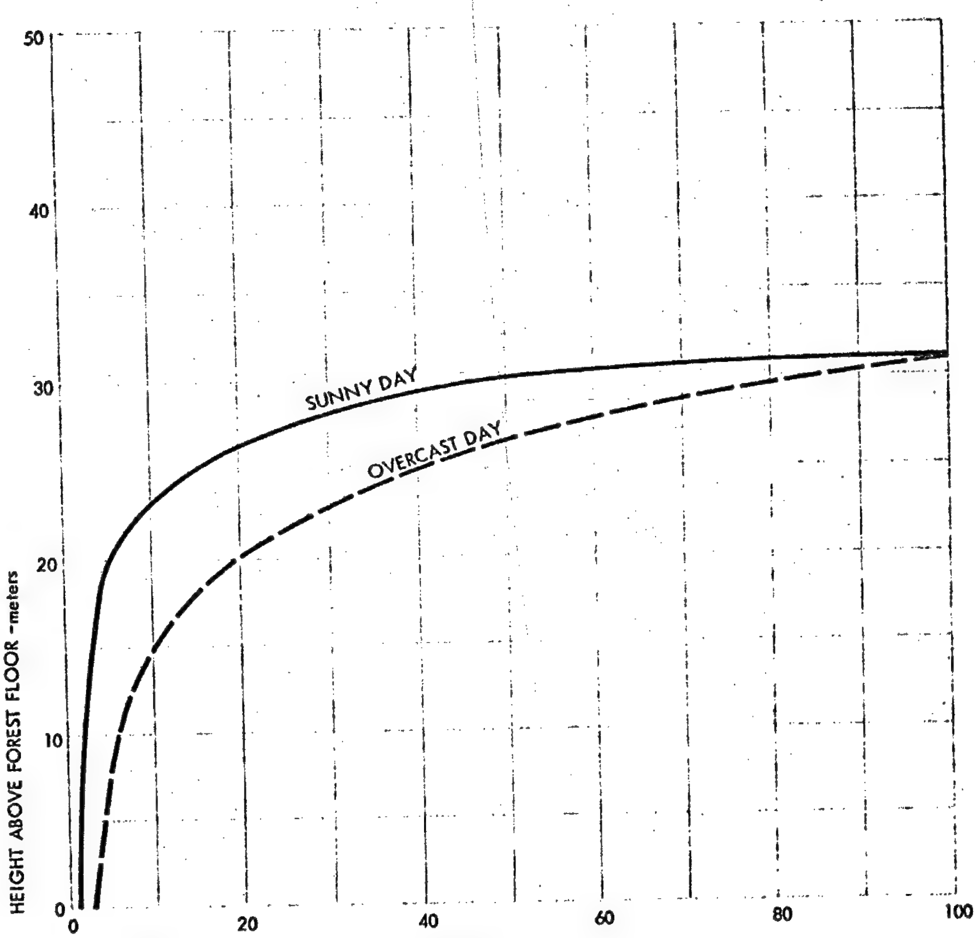
Source: Fons, et al. (1950).

Modification of the Thermal Pulse by Vegetation. Many targets would be entirely or partially shielded by trees, bushes, or other vegetation from the thermal radiation of a nuclear detonation. In Geiger (1950), Chapter 27 is devoted to the absorption of solar radiation in low plant cover; Chapter 30 considers radiation levels in old stands of trees. Figure B-61 shows the fraction of outside light reaching various heights above the forest floor in an old stand of beech trees while Figure B-62 depicts the manner in which the trees shelter the forest floor, as a function of the age of the trees. Tables B-XIII and B-XIV show some additional results.

Bruce and Downs (1956) also considers the shielding effect of trees. In this reference it was assumed that a well-foliated hardwood tree would be a perfect shield against thermal radiation from a nuclear weapon. To ascertain the transmission of radiant energy through a deciduous tree in winter, the north sky light transmitted by 35 large elm, maple, ash, cottonwood, and oak trees without leaves was measured. The average transmission was found to vary from about 65 percent just above the main crotch to about 80 percent through the upper part of the crown. These figures seem to be slightly high in comparison with the results given in Table B-XIII.

Figure B-61

DECREASE OF BRIGHTNESS IN THE INTERIOR OF A THICK FOLIAGE OF RED BEECH GROWTH

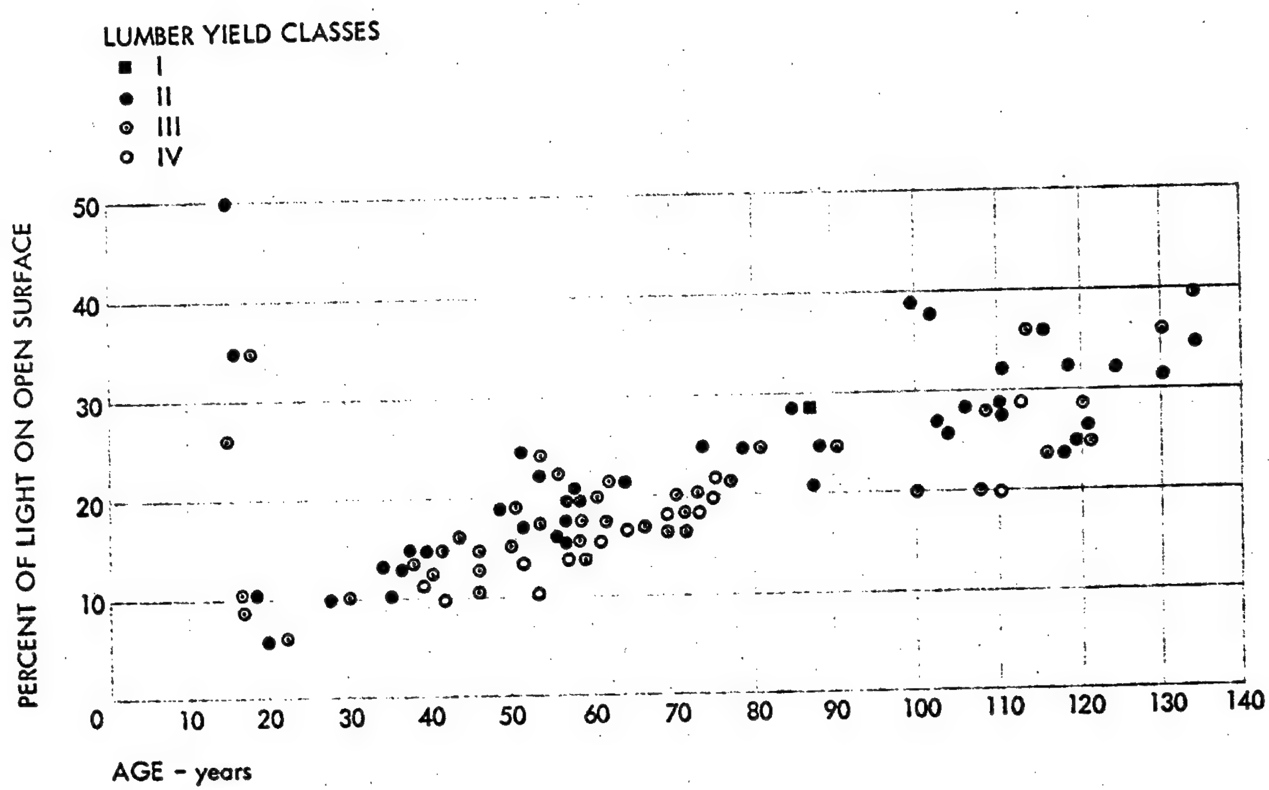


NOTE: 120 -150 year old forest of red beech

SOURCE: Geiger (1950)

Figure B-62

BRIGHTNESS IN THE INTERIOR OF PINE FORESTS AS A FUNCTION OF AGE OF GROWTH



SOURCE Geiger (1950)

Table B-XIII

ILLUMINATION ON A FOREST FLOOR

Kind of Trees (old stand)	Illumination as a Percentage of Outside Illumination	
	Leafless	Leafed Out
Deciduous		
Red Beech	26-66%	2-40%
Oak	43-69	3-35
Ash	39-80	8-60
Birch	--	20-30
Evergreen		
Silver Fir	2-20%	
Spruce	4-40	
Scotch Pine	22-40	

Source: Geiger (1950).

Table B-XIV

BRIGHTNESS IN A STAND OF TREES

Time of Measurement	Brightness in Percent of that Above Open Land		
	Coniferous Trees (A)	Mixed Trees (B)	Deciduous Trees (C)
End of April before sprouting	8%	22%	51%
End of May after sprouting	7	14	23
End of September shortly before foliage changes color	4	4	5

Source: Geiger (1950).

Effects of the Thermal Pulse on Structures. In most cases, fire in structures would not be started directly by the thermal pulse; rather, it would develop from ignited kindling fuels in proximity to or within the structures. This will be treated later in this report where the relation of thermal pulse to fire development is considered.

There is a possibility that fires would be ignited on the roofs of structures. Miller (1962) uses the criterion of 9 cal/cm^2 for the ignition of weathered shingles by a 1-kt weapon. This, of course, would have to be scaled with yield for larger weapons, and the corrections given in equation (22) should be used to adjust for the orientation of the roof with respect to the fireball.

For roofing, Capabilities of Atomic Weapons (1957) lists the data given in Table B-XV.

Classified Table B-XV concerning radiant exposure values has been deleted.

In slum areas, where the general condition of the structure is so dilapidated that the woodwork is rotten or splintered, integral parts of the building other than the roof may ignite from the thermal pulse. These might also ignite at about 9 cal/cm^2 for a 1-kt weapon according to Miller (1962), which shows this value for weathered wood siding.

As a point of interest, because of the critical dependence of the ignition of fine fuels on moisture content, it has sometimes been suggested that buildings should be left unpainted in order to absorb more moisture. Others, however, are convinced that painting is important not only to preserve the wood and limit rotting, but also because of the reflectivity of the paint.

Although it takes more than 19 cal/cm^2 by a 1-kt weapon to char white painted wood siding, once charred, even new wood will ignite at about 9 cal/cm^2; Miller (1962). Hence, structures are much more vulnerable to the thermal pulse from a follow-on weapon than from a single detonation.

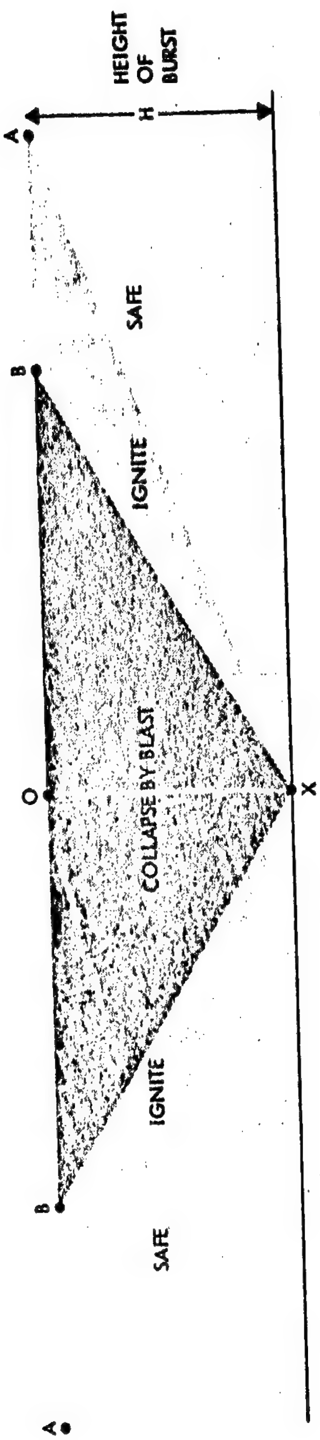
Modification of the Thermal Pulse by Structures. Thermal radiation from a nuclear detonation may enter a structure through a window or door and ignite kindling materials, such as draperies, magazines, newspapers, upholstery, or clothing. Because of the masking by window glass or screens, the window or door frame, and external structures and trees, only a fraction of the possible radiation from a fireball will strike a given point in a room.

Several studies have attempted to estimate the ultimate thermal energy impinging on kindling fuels within buildings. The geometry relating the burst point of the weapon and the window shape and location to the areas of possible ignition within the room is shown in Figures B-63 and B-64; see Broido and Trilling (1955) and Fire Research Bulletin No. 1. For a given height of burst, it is seen that for points nearer the target at X than the point B, the target will collapse from the blast wave. For the points between A and B, the thermal radiation will still be capable of starting fires although the blast wave will not affect the structure. Beyond A, the structure is safe from blast and thermal radiation. Hence, as shown in Figure B-64, the band of direct radiation from the fireball will enter the structure at a certain angle, depending upon the range and altitude of the detonation. For a given detonation altitude, if the angle subtended by the fireball is too high, the building will collapse; if low enough, the building will be safe from fire and blast; and in between, the building may ignite if the radiation falls on kindling fuels. The locus of all points between A and B in Figure B-63, when considered in three dimensions, becomes an annular region called an "effective sky ring." The size of the effective sky ring depends, of course, on the vulnerability of the kindling fuel, the altitude and yield of the atomic weapon, and the transmission factor. This idealized concept does not include shielding. Figure B-65 is an illustration of a sky ring for the ignition of a newspaper by a 60-kt weapon detonated at 1,732 feet altitude in a clear atmosphere. It is important to note that only the direct rays (those not scattered or reflected) can be considered in the sky ring concept. Pancake-shaped fireballs from outer space shots also do not apply.

In Salzberg, et al. (1960), a much more sophisticated mathematical model is developed to describe the relation of a fireball, a room, a window, and a horizontal plane two feet above the floor of the room. The significance of the plane is that all potential ignition points are

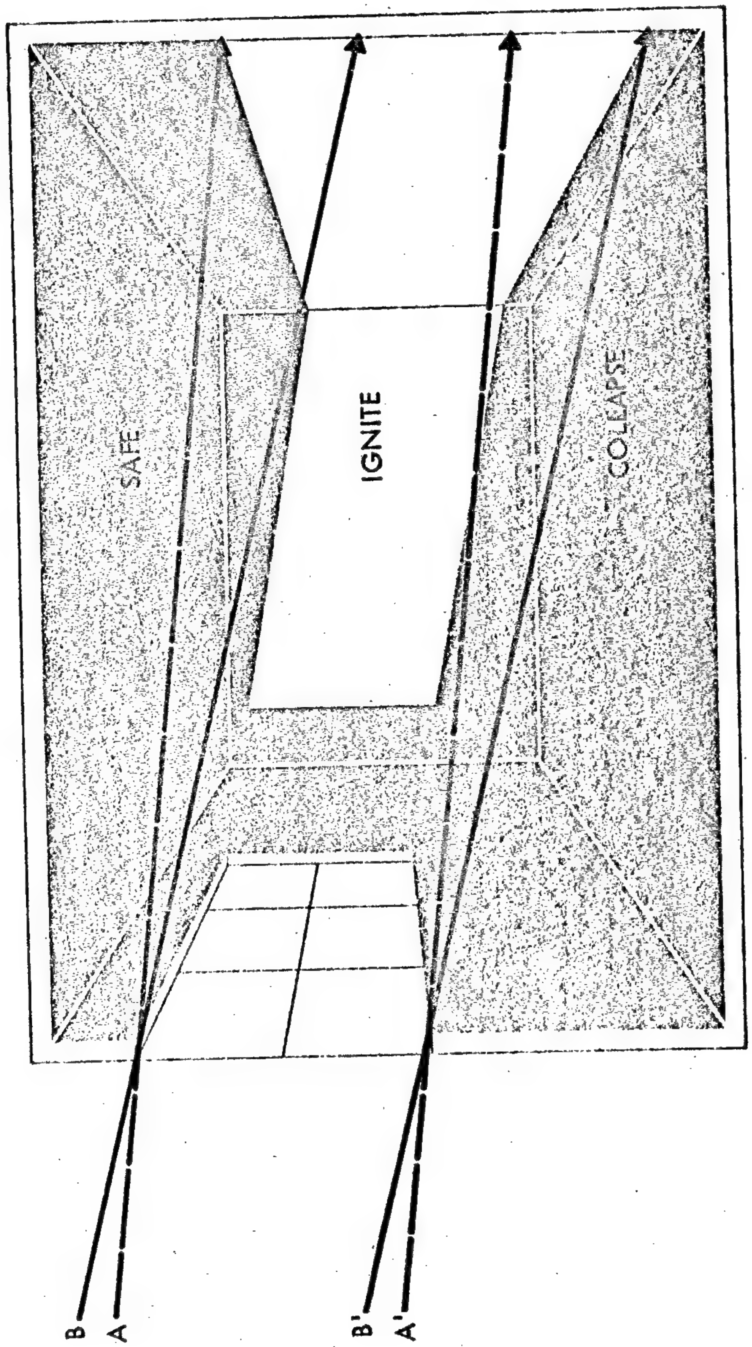
Figure B-63

CRITICAL ANGLES FOR THERMAL RADIATION EFFECTS



SOURCE: Broido and Trilling (1955)

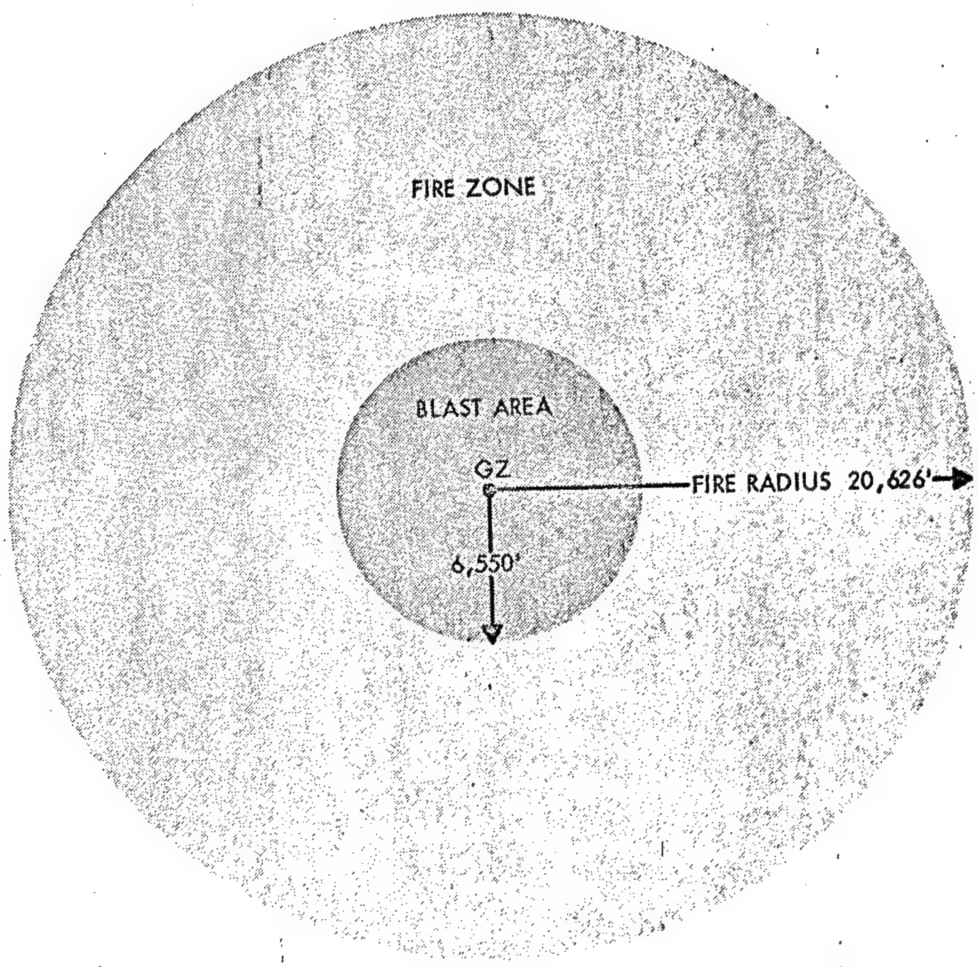
Figure B-64
CRITICAL REGION FOR THERMAL IGNITION IN A ROOM



SOURCE: Broido and Trilling (1955) and Fire and the Atomic Bomb (1954)

Figure B-65

RELATIVE SIZES OF THE BLAST AREA AND OF THE FIRE ZONE FOR NEWSPAPER (approximately a 60 kt atomic bomb explosion at 1,732 feet above ground zero)



SOURCE: Bruce and Downs (1956)

located at this height, which is about the level of upholstered furniture, bedding, and so on. Particular attention is directed to the relation of the window frame size to the apparent size of the fireball. As in the less sophisticated development, only direct rays from a spherical fireball are considered.

In Chandler and Arnold (1953), the analysis of exterior ignition points is considered. In this investigation, the modification of the thermal energy by buildings and fences is described by a sky-area factor. Ignition points (combustible materials in a position to act as a source of fire) are assumed to be located in three major exposure situations:

1. Adjacent to sides of buildings or fences and facing other buildings across the street. Exposed sky-area factor, 1/3.

2. Adjacent to sides of buildings or fences but not facing buildings or other obstructions. Exposed sky-area factor, 1/2.

3. Centrally located in large open areas. Exposed sky-area factor, 1.

If an ignition point normally requires a certain number of calories for ignition, this number is divided by the sky-factor to correct for the proximity of the point to buildings.

Although there has been criticism by Sauer (1955) of the methodology described above, no other practical method has been presented and apparently no further work is being done on the problem.

Effects of the Thermal Pulse on Cities. It is sometimes assumed that fires will be ignited by the thermal pulse within a certain radius from ground zero. Beyond this radius it is assumed that fires will develop only from fire spread from the initial area. This approach is an oversimplification and obviates the study of ignition point densities within the target area and their development into mass fires. It is a crude index of the extent of the area within which some thermal damage may be expected; it does not suggest the amount of damage nor describe the distribution of damage within the area.

Many different criteria have been used for ignition radius. Using the data from the Hiroshima and Nagasaki weapons, Miller (1962) suggests that for a 1-kt weapon the initial fire radius would extend to about 6 cal/cm^2 for the vertical component of the energy and 9 cal/cm^2 for roofs

(weathered shingles). These correspond respectively to 8 and 12 cal/cm^2 for a 20-kt weapon, using Miller's scaling laws. Miller points out that the energy corresponding to the radius of primary ignitions at Hiroshima appears to be closely related to that required to ignite colored fabrics.

Jewell and Willoughby (1960) have used an initial fire radius determined by 3 cal/cm^2 radiation from a 20-kt weapon. This figure seems very low when compared with the data presented by Miller and with the graphs in Figures B-31 through B-38. It is probably due to a misinterpretation of the energy criterion used by the forest service in Sauer, et al. (1953) to determine the density of primary ignitions.

The manner in which built-up areas would modify the thermal pulse prior to reaching a target element has never been considered; hence, the quantitative importance of this effect is unknown. All damage assessment models have ignored the possibility that scattered or reflected radiation could ignite fuels. The problem, of course, is a very difficult one. Perhaps the scattering of thermal radiation in urban areas, particularly in high-rise cities, could be introduced by developing data similar to the attenuation of radiation by forests (see Figure B-61). This has never been done.

Relationship of the Thermal Pulse to the Ignition of Fires. After a thermal pulse from a nuclear weapon has been modified by the atmosphere, weather, topography, vegetation, and structures in the target area, it will eventually strike fuels which are susceptible to ignition. The details of the modification of the thermal pulse and the requirements for various kindling fuels to ignite have been described previously. The models devised to estimate the density of primary ignitions which will develop into fires will now be discussed.

To clarify the ideas, a few commonly used definitions will first be given; see Bruce and Downs (1956):

Potential Ignition Point - A quantity of kindling fuel which has some chance (between 0 and 1 probability) of being ignited and of starting a primary fire.

Primary Fire - Fire spread from a primary ignition and constituting a hazard to life or property, or both.

Primary Ignition - Kindling of fuel into flaming or glowing combustion of more than momentary duration by thermal radiation from the fireball of an atomic weapon.

<u>Primary Ignition Point</u> - A potential ignition point in position to receive thermal radiation from all parts of its effective sky ring.

<u>Effective Sky Ring</u> - A horizontal washer-shaped ring in the sky in which the explosion of an atomic bomb would ignite a particular type of kindling fuel on the ground beneath the geometric center of the ring, without excessive blast damage to frame buildings adjacent to the fuel.

The effective sky ring concept was introduced on page B-117 in relation to potential ignition points within buildings. The concept applies equally well, however, to external potential ignition points.

In Bruce and Downs (1956), a method is outlined for using the sky ring to predict the ignition of a kindling fuel element located within a room. In actual surveys, potential ignition points were first identified. The percentage of the effective sky ring which was in view through the windows from each of these points was estimated by two different techniques. The first technique made use of photographs taken through the window from each potential ignition point. The second technique made use of a special purpose instrument which permitted the on-site estimate of the window masking and exterior shielding afforded by other buildings and trees. In actual tests, the instrument technique was found to be much less reliable than the photographic technique. Corrections were made for the transmission of the energy through window screens and through combinations of window glass and screens as shown in Table B-XVI. It was assumed that energy filtering through trees would be reduced to 25 percent of its initial value in the winter and would be entirely blocked in the summer. The technique developed in this study was applied in surveys in Boston and Detroit; the results are described in Appendix D.

Because of the difficulties in collecting adequate statistical data to support the method developed in Bruce and Downs (1956), an analytic method was derived to study the probability of the occurrence of a fire in a structure; see Salzberg, et al. (1960). In this theory, light fuels, such as curtains and magazines, are not included because of the uncertainties in predicting their ultimate location after burning or displacement by the blast wave. It is assumed that other potential ignition points, such as upholstered chairs or davenports and bedding, are randomly distributed in a horizontal plane two feet from the floor--the average elevation of most furniture. It is also assumed that the probability of a particular number of potential ignition points existing in a room has a Poisson frequency distribution. Arguments are given to justify these assumptions. Masking of the fireball by windows is analytically formulated

Table B-XVI

CRITICAL IGNITION ENERGY VALUES OF COMMON MATERIALS EXPOSED, WITH AND WITHOUT GLASS AND SCREENS, TO THE THERMAL RADIATION OF A 60-KILOTON ATOMIC BOMB[a]
(Calories/cm^2)

Kindling Fuels	Critical Ignition Energy Values: Direct Exposure	Window Screen	Glass Pane	1 Glass, 1 Screen	2 Glass Panes	2 Glass, 1 Screen
Newspaper	3	4	5	8	9	14
Cotton, oiled, dry rag	3	4	5	8	9	14
LIFE magazine cover	3	5	6	9	11	16
Paper, office, thin	4	5	6	9	11	17
Paper, waxed, thin	4	5	6	9	11	17
Paper, crepe	4	5	7	10	12	18
Paper, mimeograph	4	6	7	11	13	20
Paper, school composition	4	6	7	11	13	20
Paper, pamphlet, book	4	6	7	11	13	20
Cotton, chenille	4	6	8	12	14	21
Paper, general office	5	7	8	12	15	22
Paper, bond typing	5	7	9	13	16	24
Paper, light wrapping	5	7	9	13	16	24
Paper, Kraft	5	7	9	14	16	24
Paper, window shades	5	7	9	14	16	24
Cotton, oiled window shades	5	8	9	14	17	25
Canvas, colored, awning	5	8	9	14	17	25
Cotton, scrub mop (dry)	6	9	10	16	19	28
Cotton, towelling	6	9	11	16	19	29
Wood, decayed	6	9	11	16	20	29
Cotton, light canvas	6	9	11	16	20	29
Cellulose sponge, dry	6	9	11	17	20	30
Paper, wall (in rolls)	6	9	11	17	20	30
Cotton, corduroy	6	10	12	17	21	31
Paper, drafting blueprint	7	10	12	18	21	32
Rayon, coat lining	7	10	12	18	22	32
Cotton, Venetian blind strap	7	11	13	19	23	35
Cotton, bedding	7	11	13	20	24	36
Cotton, rug, string	8	11	14	20	25	37
Rayon, clothing	8	11	14	21	25	37
Cotton, clothing	8	12	14	21	26	38
Cotton, denim	8	12	14	21	26	38
Cotton, canvas, medium	8	12	14	22	26	39
Paper, maps, heavy	8	12	14	22	26	39
Fiberboard cartons	8	12	15	22	26	40
Broom straw	8	12	15	22	27	40
Acetate, clothing	9	13	16	23	28	42
Cotton, drapery	9	13	16	23	28	42
Cotton, curtains	9	13	16	24	29	43
Acetate, curtains	9	13	16	24	29	43
Cotton, table linen	9	13	16	24	29	44
Paper, greeting cards	9	13	16	24	29	44
Wood, excelsior	9	14	16	25	30	44
Cotton, overstuff chair cover	9	14	16	25	30	44
Paper, light cardboard	9	14	17	25	31	46
Paper, light Bristol	9	14	17	25	31	46
Cotton, canvas, heavy	12	18	22	32	39	59
Paper, woven rug	13	19	23	34	41	61
Books, cloth binding	13	19	23	34	41	61
Wool, blanket	13	19	23	34	41	61
Wool, clothing	13	19	23	34	41	61
Cotton, tapestry upholstery	16	23	28	42	51	76
Burlap	20	30	36	54	65	98
Rubberized rain coat	20	30	36	54	65	98
Building paper, waterproof, black	22	33	40	59	72	107
Wool, mohair	24	36	43	65	78	117
Wool, frieze	24	36	43	65	78	117
Rubberized canvas	25	37	45	67	82	122
Wool, rug	35	52	63	94	114	171

[a] Laboratory tests were on materials conditioned at 80°F, 50 percent relative humidity. CIE values rise with increasing moisture content. CIE values for direct exposure in this table are values found in field tests when available; when field test results were unavailable, laboratory CIE values were multiplied by the average laboratory/field factor 1.29 (see footnote 5) to obtain the "direct exposure" values. At shot time in the field tests the air was at 63°F and 19 percent relative humidity.

SOURCE: Bruce and Downs (1956).

and introduced into the probability calculations. Shielding by external objects is not included in the formulation although attenuation by window glass or screens (see Table B-XVI) and by the atmosphere (see Appendix A) are considered. The entire model, together with its extension to fire development processes, has been programmed as a subroutine on a high speed computer at Armour Research Foundation. Work is continuing on this project under a current contract with the Defense Atomic Support Agency.

In the two preceding studies, attention has been directed to thermal energy striking fuels within a structure. It is important to remark that the work under way at Armour Research Foundation does not include, at the present time, the possibility of exterior ignition points. According to other studies--for example, Sauer, et al. (1953) exterior ignition points might create a serious fire hazard in case of nuclear attack.

In Chandler and Arnold (1953) a method is developed for tallying potential exterior ignition points and assigning them a weighting factor depending on the amount of fuel in the ignition point and the exposure of the point to the sky. The following excerpt describes the technique:

> "The smallest fuel unit recognized as an ignition point had an area of approximately 1.5 sq. ft., equivalent to a folded newspaper. Larger areas of fuel were tallied in multiples of this basic unit except that trash piles with an area of 15 sq. ft. or more were tallied separately and counted as 10 ignition points regardless of size. Trash cans and news stands were also tallied separately and counted as single ignition points. These exceptions were based on the probable effect of scattering of ignited fuels by blast winds.
>
> "The number of ignition points per fuel cumulation then is the number of fuel units multiplied by sky-area factor."

The sky-area factor was defined earlier in this appendix and is a number (1/3, 1/2, or 1) which estimates the amount of exposed sky at the potential ignition point. Some of the results of the surveys in various cities are shown in Table D-VI in Appendix D.

As an extension to the preceding work, Sauer, et al. (1953) relates the data from the surveys to the thermal energy required for the ignition of materials. The results are no longer directly useful since the ignition energies were based on limited field data from tests with weapons in the kiloton range of yield. To achieve a conservative approach, the number of primary ignitions was calculated on the basis of all those exterior kindling fuels which ignite at energies of 3 cal/cm^2 or less. If the energy requirement had been set at a higher amount, more ignitions

would have been tallied and the density of ignitions would have been greater, making the fire threat more serious. This is important since the study (and other succeeding investigations) used the 3 cal/cm^2 criterion to define the radius within which the target area would be destroyed by the fires started from the initial thermal pulse; see, for example, Jewell and Willoughby (1960). Obviously, a higher cal/cm^2 energy requirement in this case would have shrunk the radius of destruction and showed less damage caused by fires, which emphasizes the error in using the 3 cal/cm^2 criterion for the radius of burnout. Sauer (1955) criticizes the definition of probability of ignitions used in Chandler and Arnold (1953). A much more sophisticated probabilistic model is outlined by Sauer. With respect to the shielding of ignition points by buildings, it is assumed that fuel concentrations are random with respect to time and space and hence the blast moves as many fuels away from favorable positions as it moves into these positions. However, no practical method of using this probability model is described. Hence, in spite of its weaknesses, the method given in Chandler and Arnold (1953) remains the only feasible approach to the problem of estimating exterior ignition densities which was found in this literature survey.

One other possibility for calculating the density of fires ignited by the thermal pulse of a nuclear detonation has been described in Broido and Trilling (1955). The approach is to partition a target area into those subdivisions which appear to have approximately the same fire susceptibility characteristics. Probabilities of their being destroyed by fire could then be assigned by experienced assessors. By further partitioning each of the regions into smaller subdivisions, probabilities of destruction of the smaller areas could also be estimated and perhaps with less error (in the aggregate) than estimates made for the larger subdivisions. This theory assumes that if the subdivisions are small enough, good estimates of destruction probabilities can be made by men experienced in fire fighting techniques. The mathematics are developed by combining the probabilities of destruction for the subdivisions into a probability of destruction for the entire target.

Although Fons, et al. (1950) considered in some detail the ignition of forest areas by a nuclear detonation, none of the work on ignition of materials had been completed at the time the document was written. In addition, only fission weapons were considered at that time, and the difference in scaling to larger weapon was not incorporated. No other studies have been made of the ignition of forested areas with the exception of those which assume a certain ignition radius based on the ignition of some fine forest fuel. Shielding of potential ignition points by leafy green vegetation, the distribution of ignition points, the probabilities that they will develop into fires in heavier forest materials (which are much less sensitive to humidity changes), and many other factors have been ignored in research activities.

Appendix C

RELATIONSHIP OF THE PHYSICAL ENVIRONMENT TO THE NUCLEAR FIRE PROBLEM

The physical environment as defined here includes the effects of weather and topography. Before considering the individual effects of these two factors, it should be mentioned that their relationship to fire spread rates and civil defense requirements has been described qualitatively in Civil Defense Urban Analysis (1953). In this document, the burning potential is defined as a function of relative humidity and wind velocity at 20 feet above ground as shown in Table C-I. For steep terrain Table C-II applies. Entering these qualitative expressions for burning potential into Table C-III gives an approximation of the rate of spread of fire and its implications for civil defense. These evaluations are based on forest fire experience. For fires in wildlands, more quantitative estimates can be made of the effects of terrain and weather, as well as fuel type, by use of tables and graphs issued by the Forest Service; see, for example, Fireline Notebook (1960). For calculating fire spread rates, these devices are fairly reliable since they are based on past history of the actual fire and existing weather conditions.

Two current projects under study by the Forest Service endeavor to relate all of the parameters of fuel types, topography, and weather to fire behavior. The first study attempts to correlate various parameters with test fires started in forested areas. The second study involves a comprehensive statistical analysis of data derived from case histories of forest fires; documented conflagrations, both urban and rural; and extensive interviews with fire chiefs. From these data, computer correlations will be made to identify environmental parameters which affect the behavior of large fires. One objective of this study is to develop input data for a specific predictive model of mass fire spread which is being developed under a companion research project at United Research Services.

The Application of Weather and Climate Statistics to the Analysis of U.S. Vulnerability to Nuclear Fires

Weather and climate enter into the nuclear fire problem in several important ways. The transmission of the thermal energy from the burst

Table C-I

BURNING POTENTIAL IN RELATION TO RELATIVE HUMIDITY
AND WIND--LEVEL TERRAIN
(Slopes Less Than 20 Percent)

Wind Velocity at 20 Feet Above Ground (miles (per hour)	Relative Humidity			
	Above 40	26-40	15-25	Below 15
0-12	Low	Moderate	Moderate	Dangerous
13-24	Moderate	Dangerous	Dangerous	Critical
Above 24	Dangerous	Dangerous	Critical	Critical

Source: Civil Defense Urban Analysis (1953).

Table C-II

BURNING POTENTIAL IN RELATION TO RELATIVE HUMIDITY
AND WIND--STEEP TERRAIN

Wind Velocity at 20 Feet Above Ground (miles per hour)	Relative Humidity			
	Above 40	26-40	15-25	Below 15
0-12	Moderate	Moderate	Dangerous	Critical
13-24	Dangerous	Dangerous	Critical	Critical
Above 24	Critical	Critical	Critical	Critical

Source: Civil Defense Urban Analysis (1953).

Table C-III

BURNING POTENTIAL AND FIRE EFFECTS

Burning Potential	Type and Rate of Spread	Civil Defense Requirement
Low	Slow-burning fires, no spotting.	No direct danger; fire can be controlled at will; control action can be on an individual structure basis.
Moderate	Fires burn rapidly, individual building fires combine to form an area fire.	Organized action needed to corral fire and confine to area originally ignited.
Dangerous	Fast-moving fires which spread readily over large areas and throw spot-fires ahead 1/4 to 1/2 mile.	Probability of mass damage high. Aggressive, organized action of all available personnel and equipment is essential to limit mass damage.
Critical	Conflagration-type, fast-moving fire fronts and firestorm highly probable.	Personnel and equipment should be evacuated from in front and from near the flanks of such fires. Organized action only on rear and flanks with plans to attack head when changes in fuel or burning conditions permit.

Source: Civil Defense Urban Analysis (1953).

to the target area (see page B-16) is strongly affected by the presence or absence of clouds, as well as their types and locations; by visibility; by surface reflectivity; and by other meteorological factors. The ignitability of materials in the target area and the spread of the fire after ignition by the thermal pulse are directly influenced by the weather conditions at the time of the attack and during the time interval preceding the attack. The important parameters here are the wind, temperature, humidity, precipitation, and atmospheric stability. Weather also plays a role in the effectiveness and feasibility of certain types of countermeasures, such as the generation of smoke clouds. Finally, postattack recovery could be strongly influenced in certain areas by floods arising from the destruction of watersheds.

For illustrative purposes, the discussion in this section has been predominantly directed to the interpretation of weather statistics for the problem of predicting transmission of the atmosphere and area of initial burn. However, the arguments are equally applicable to the problems of fuel moisture content, fire spread, and other weather-dependent variables.

For evaluating an individual target area, the following questions are of prime importance. What is the largest area of ignition or of flash damage by the thermal pulse which might be expected? What is the smallest area it is reasonable to expect? What is the "average" value? Answers to these questions are needed, of course, to establish the initial conditions for the ultimate problem of fire spread and over-all damage. They are also required for determining shelter requirements, for planning initial countermeasures and their deployment, for assessing initial casualties, and for determining the risk of damage from attacks against nearby target areas. Since the radius within which primary ignitions occur is a function of the atmospheric transmission factor, among other things, the average and extreme values of this variable are required. As will be discussed in more detail below, the fact that the transmission is a function of many variables means that the use of simple climatic averages of weather observables may not suffice, and, depending on the accuracy desired, further computational refinements are required.

For evaluating the problem on a national scale, the following questions require answers. What is the total expected initial area of damage (average and reasonable extremes) if the timing of the attack is totally unrelated to weather conditions? What is the largest possible initial area of damage if the attack is precisely tailored to extreme weather conditions? The answer to the latter question is important in determining whether or not there is sufficient incentive for such an

attack to warrant further detailed study.* The necessity for averaging correctly is more important in nationwide summaries than in the individual target case because of the widely varying seasonal patterns of weather across the country. Any computation of average or extreme conditions must take into account the simultaneous values of the parameters of interest rather than accumulate the effects of individual averages or extremes.

A wealth of precedent exists, of course, for the application of climatic data to military strategy and planning. This is especially true of World War II, during which the AAF Weather Service prepared over 1,500 such studies; see Jacobs (1947). These studies are distinct from the normal military weather observation and prediction for specific near-term time periods, which are used for operational purposes. In applied climatology, the purpose is to establish distributions, probable averages, or probable limits for a certain weather variable or set of variables (often as they occur simultaneously) over a certain time period at a given geographical point or region.

There may well be more raw data on weather than on any other single subject, the data being the product of the largest physical information gathering system in the world. In addition, the newer radar and satellite techniques, which will be discussed later, are adding enormously to available meteorological data. Although satellite data will have a significant impact on the fire problem, their use will be primarily as an augmentation of conventional data which are essential for most phases of the analysis. Conventional data may be replaced gradually by satellite data in some phases of meteorological analysis as the correlations between satellite data and surface observations become clarified. The problem at hand is to determine the adequacy of the data available and the appropriate methods for any further analysis.

Existing weather data go back many years. A daily bulletin of international observations, for example, has been published since 1875.

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* During World War II, the incendiary attacks by the United States on Tokyo were directly keyed to the weather. This was accomplished by first determining the type of weather which created "good fire days" in North Carolina. Then, ten years of weather data for Tokyo were reviewed and "good fire days" were found to occur from January through March--seldom in June through October. This information was used in planning the highly successful incendiary attacks on Japan; see Bond (1946).

This contains surface and upper air observations from weather stations and ships distributed over much of the world. The bulk of the available data is obtainable in punched card and other forms at a centralized climatological facility in Asheville, North Carolina. "This facility consists of the National Weather Records Center operated by the U.S. Weather Bureau, with major support from the U.S. Navy, and the Data Processing Division of the Climatic Center, U.S. Air Force, operated by the Air Weather Service." An excellent description of this facility and its services is given by Barger (1960).

Much of the above and other more specialized weather data have been analyzed to determine specific physical relationships in the atmosphere. (Some of the data that are applicable to the atmospheric transmission problem have been described previously.) Meteorological data have also been analyzed from a climatological standpoint for a very large number of variables. The broadest summary of these is probably that of Visher (1954), which presents nationwide isolines of the major weather variables on an annual, monthly, and, in some cases, weekly and daily basis; see also Climate and Man . . . (1941). Figure C-1 presents a climate summary based on these two references for the available weather variables which are most closely related to the transmission problem. The curves illustrate the percentage of cities larger than 100,000 population[1] having given weather conditions for the indicated number of days per year. As an example, 30 percent of the cities have, on the average, 61 days or more in which there is snow on the ground (at least one inch deep). This gives some idea of the importance of the various weather conditions. (A more exact indication would be given by conversion of the number of cities to total population.)

The specific weather factors required to establish a transmission factor or, perhaps better, an ignition radius, climatology* include at least the following: visibility, cloud cover, cloud height, cloud tops, cloud albedo (reflectance) or transmissivity, and surface albedo. Ideally, the relationships should be found for several burst altitudes and, if ignition radius is used, for several yields. Use of the ignition radius rather than the transmission factor might be preferable. (For the above-cloud case a simplification can be made by the use of the solar insolation measurements--a method illustrated later.)

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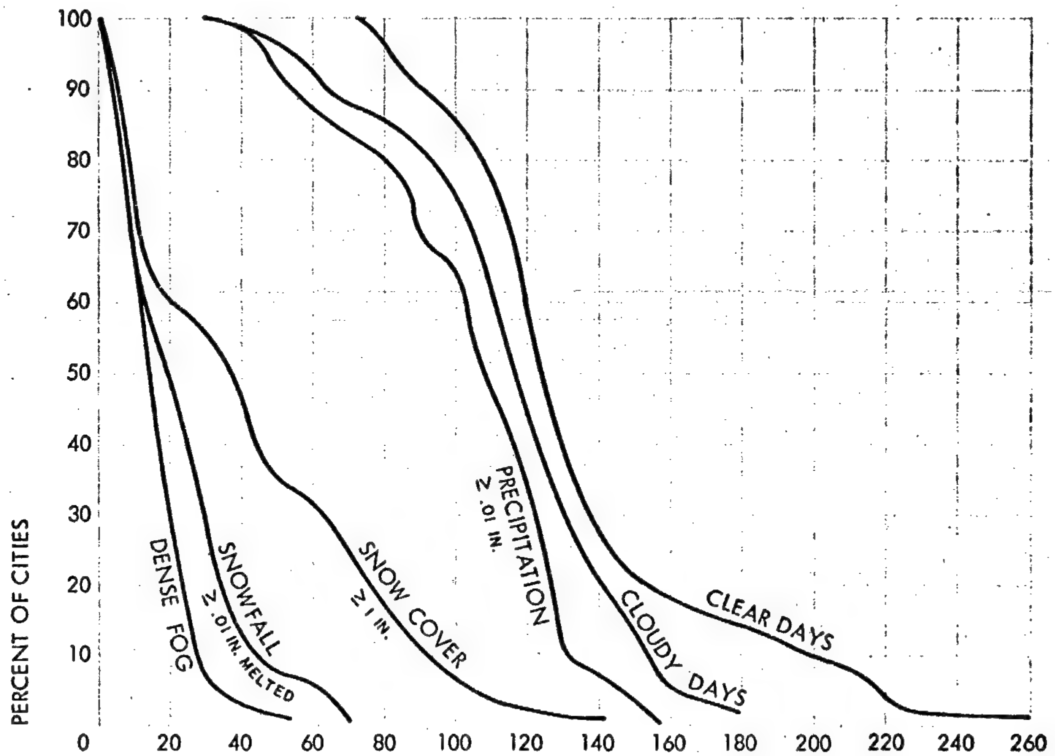
1. U.S. Census of Population: 1960, Number of Inhabitants, United States Summary (1961).

* As used here, the climatology of a variable, e.g. cloud cover, is the study of the averages and extremes of that variable for a given time period.

Figure C-1

CLIMATE SUMMARY
(cities larger than 100,000 population)



AVERAGE NUMBER OF DAYS PER YEAR

SOURCES: Climate and Man... (1941), Visher (1954) and Stanford Research Institute

An analysis to this level of detail has not been done. In fact, without further study, it is not known what level of detail is appropriate to the nuclear fire problem. There are analyses, however, which have peripheral application to the problem. Certain of these are illustrated below to indicate the range of some of the variables involved. These studies differ from the type of study required to establish a transmission factor or ignition radius climatology in that they use only one directly measured weather variable. For the fire problem, a complicated function of at least the six variables mentioned above (as they occur simultaneously) is required. The first three variables--visibility, cloud cover, and cloud height--are regularly reported weather observables; the others are discussed elsewhere.

The meteorological study which is probably most closely related to the nuclear fire problem under consideration here is that of Duckworth, et al. Meteorological Feasibility of Thermal Radiation Attenuation Clouds (1953). In analyzing the feasibility of such countermeasures, a detailed examination was made of the pertinent weather conditions, with primary emphasis on four cities. Figures C-2 and C-3 give examples of the analysis of "ceiling," one of the variables applicable to atmospheric transmission. Probably the main conclusion to be drawn from these graphs is the potential importance of measuring the values simultaneously and at frequent intervals. This method of measurement is a necessity if a nationwide summary is desired because the wide divergence in value assumed by the variables precludes the use of average values as an accurate indication. Duckworth, et al. (1953) also has a detailed summary of the availability of weather data appropriate to such a study. In 1953, 97 of the 106 cities with population over 100,000 had adequate surface observations and 94 of the cities had facilities for upper air observations sufficiently close to be considered useful. Information of this type should be further analyzed and updated if a decision is made to put a significant effort into a nuclear fire climatology. Figure C-4 presents similar information on the variation of visibility, this time for 19 major cities; see Whittaker (1961).

Figures C-1 through C-4 have indicated the likelihood of limited visibility and low ceilings. Another factor of importance in the case of lower altitude bursts, as mentioned previously, is that of broken and multilayer clouds. Figure C-5, from Serebreny and Blackmer[1] presents some data for this case for July 1958. The figure shows the percent of time that various amounts of sky cover were reported as multiple layers (middle and high clouds,

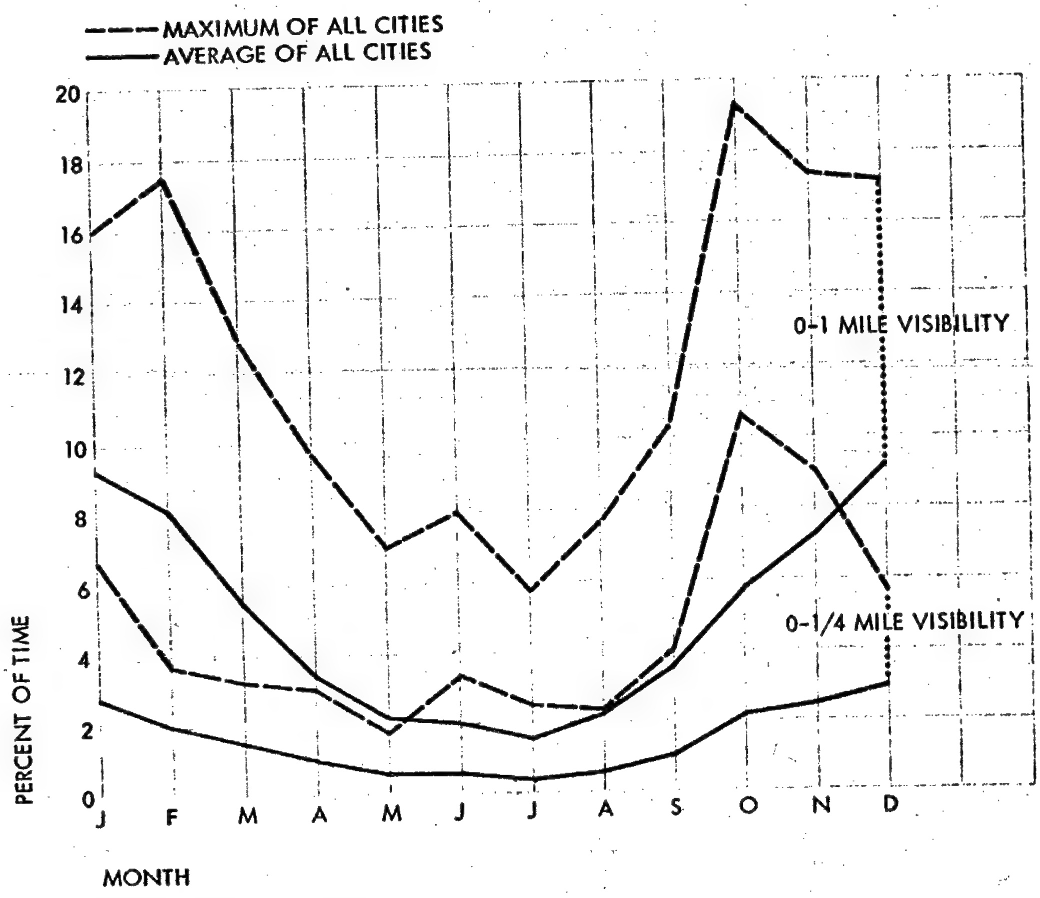
1. "An Investigation to Establish the True Nature of Cloud Cover" (1962).

Classified Figure C-2 on frequency
of ceilings has been deleted.

Classified Figure C-3 on diurnal frequencies of ceilings has been deleted.

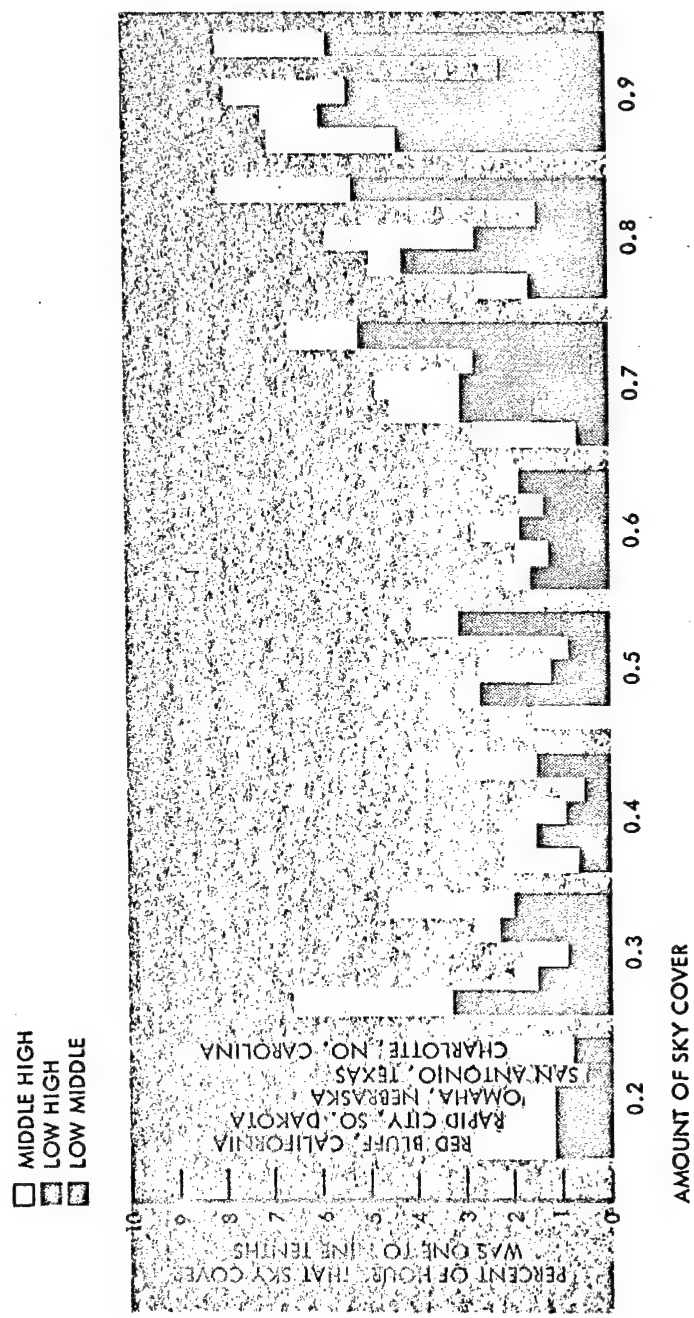
Figure C-4

FREQUENCY OF OCCURRENCE OF ≤ONE-MILE VISIBILITY
(19 selected cities)



SOURCE: Whittaker (1961)

Figure C-5
FREQUENCY OF MULTIPLE LAYERS IN VARIOUS CLASSES
(July 1958)



SOURCE: Serebreny and Blackmer (Report No. 4, 1962)

low and high clouds, or low and middle clouds). The percentages are in terms of the number of hours that each class occurred as compared to the total number of hours that the sky cover was one-tenth to nine-tenths. This total number of hours varied from station to station--for example, Omaha had 269 hours (or 36 percent) and San Antonio had 378 hours (or 51 percent) of broken clouds. The data were compiled from the "WBAN-10 Forms" normally used for reporting weather observations. As indicated in Serebreny and Blackmer (1962) these figures actually represent lower limits on the frequency of multiple cloud layers because of the difficulty in observing upper layers visually from the ground in the presence of a lower cloud layer.

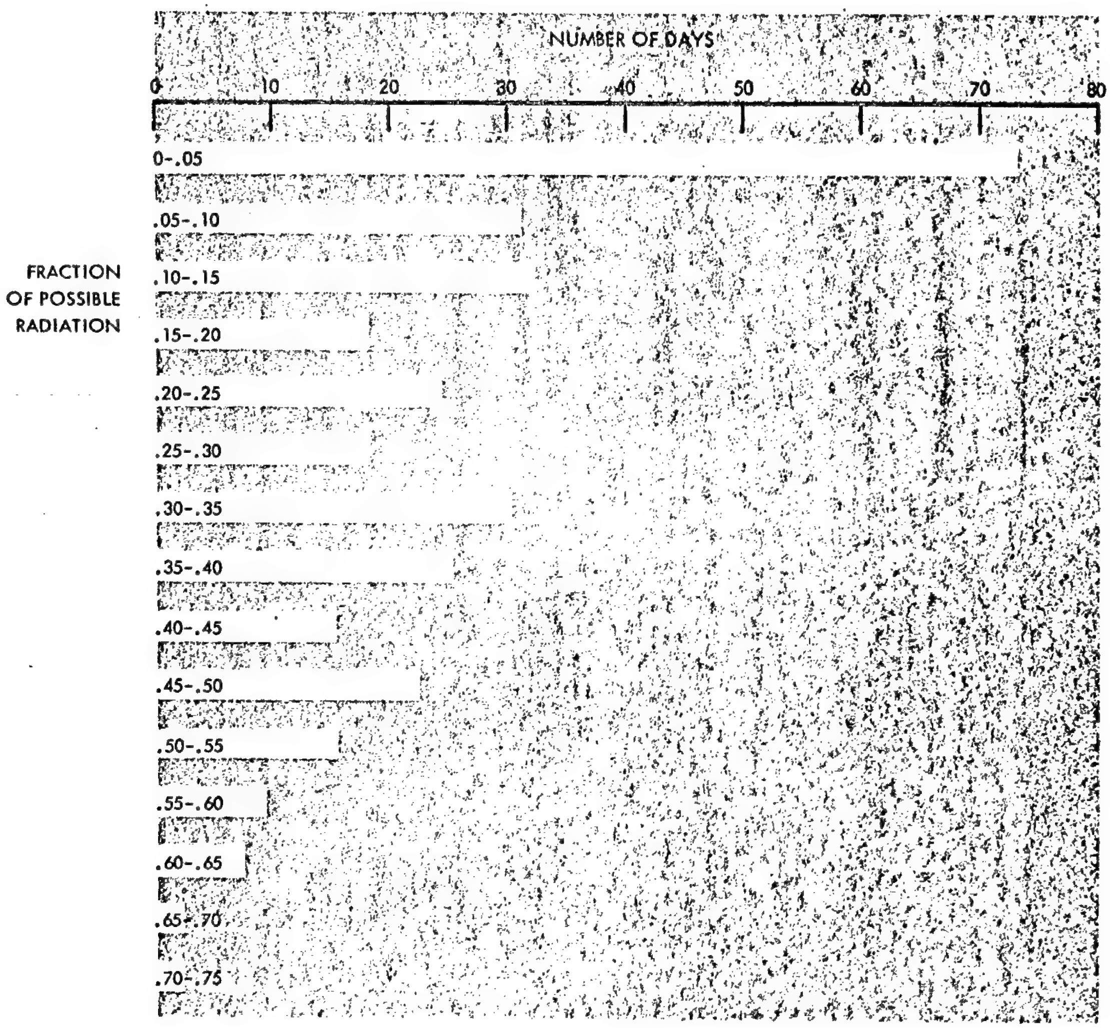
While the above studies and others like them are of use in illustrating the importance of various weather parameters, they are not sufficient to form a transmission factor climatology of adequate depth for use on a nationwide basis; further analysis of the punched card and taped data mentioned above would probably be required. For the case of a low altitude burst, however, computations of transmission factors for a wider variety of weather conditions beyond those presently available would have to be made. For the case of the high altitude burst above the clouds, the situation is less complicated. The following discussion illustrates how the variation of ignition radius may be approximately determined for daytime weather conditions.

The Weather Bureau performs hourly measurements of total solar insolation (sum of direct and diffuse) on a horizontal receiver at many stations throughout the United States. These measurements can be used to determine an approximate transmission factor by taking the ratio, R, of the measured insolation to the known value of the insolation outside the earth's atmosphere. Figures C-6 and C-7 indicate the distribution of this factor for New York and Seattle over a year-long period. The figures are based on data and computations obtained from the National Weather Records Center at Asheville, North Carolina; see Passell (1963) and Hourly Solar Radiation Data (1962). The data shown in the graphs apply to the first hour after sunrise; similar curves could be drawn for all of the daylight hours. Note, for example, that in the case of New York, 73 (or 20 percent) of the days had 5 percent or less transmission at this time of day. This corresponds, in the case of a horizontal receiver, to an ignition radius of two miles or less for a 10-mt burst at 30,000-foot altitude (see Figure B-16).

Figure C-6

DISTRIBUTION OF SOLAR RADIATION — NEW YORK

NEW YORK CITY, NEW YORK
JUNE 1, 1960 - MAY 31, 1961
1 HOUR AFTER SUNRISE
SUN ELEVATION ≤ 14°

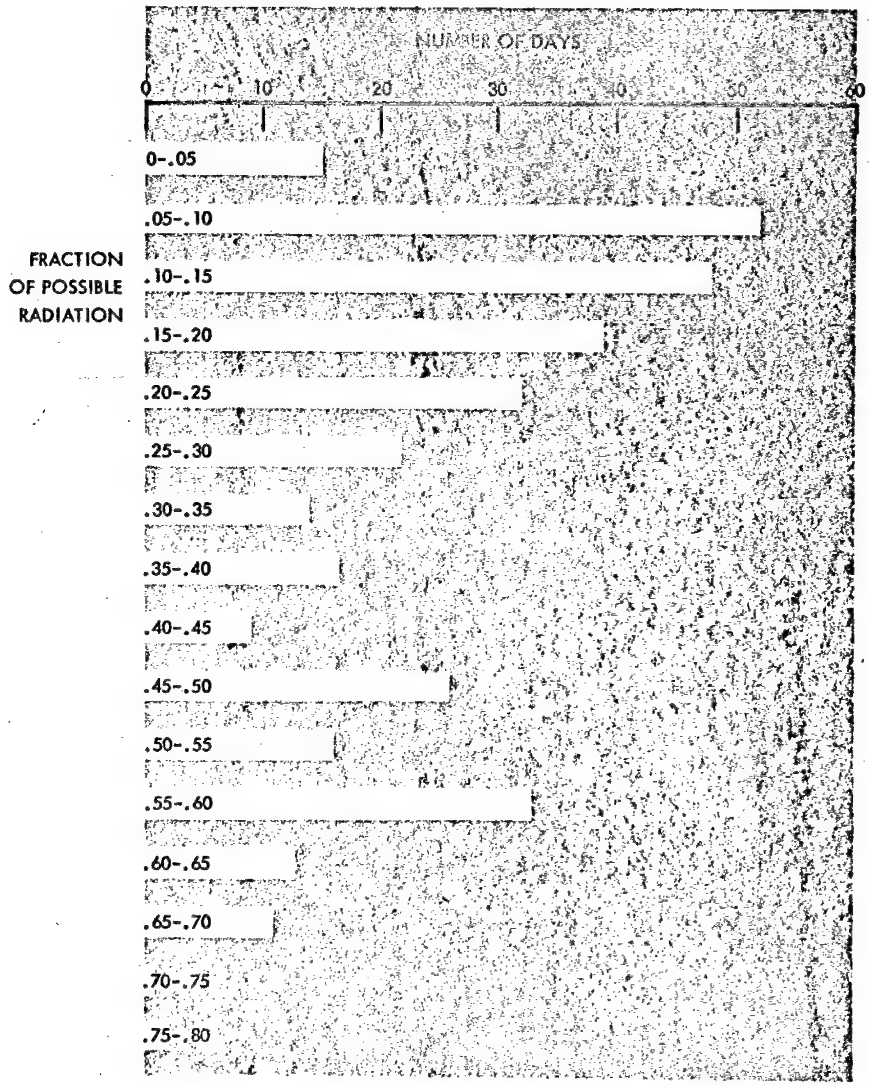


SOURCES: Hourly Solar Radiation Data (1962) and Stanford Research Institute

Figure C-7

DISTRIBUTION OF SOLAR RADIATION— SEATTLE

SEATTLE, WASHINGTON
JUNE 1, 1960 - MAY 31, 1961
1 HOUR AFTER SUNRISE
SUN ELEVATION ≤ 14°



SOURCES: Hourly Solar Radiation Data (1962) and Stanford Research Institute

A rough idea of the variation of transmission with time of day for several cities can be obtained from Figure C-8. Here the average percent of possible sunshine for the months of June through August is given as a function of hour of the day. This has been adapted from Visher (1954) by shifting the curves to put them on a single time base. While the values here cannot be directly converted to ignition radii, the curves do give an indication of the importance of putting transmission values on a common time reference.

A better picture of the potential variation of ignition radius with time over short periods can be obtained by plotting ignition radius versus hour from the insolation data of the Hourly Solar Radiation Data (1962). Examples of this are shown in Figures C-9 and C-10. Values of ignition radius shown are for dry pine needles (see page B-46) for a burst at 30,000-foot altitude under the assumption that the burst is above all clouds. The two figures give an indication of the extremes in the patterns of variation. The first, Figure C-9, is for the month of March, during a variable season, and applies to a horizontal receiver. The second is for the less variable month of July and applies to an optimally oriented receiver. Part of the difference in the two graphs is thus due to changes in weather and part due to changes in orientation of the receiver. A 20-mile ignition radius, for example, for an optimal receiver corresponds to a 12.2-mile ignition radius for a horizontal receiver under the computational approximations and weather and burst conditions being used here.

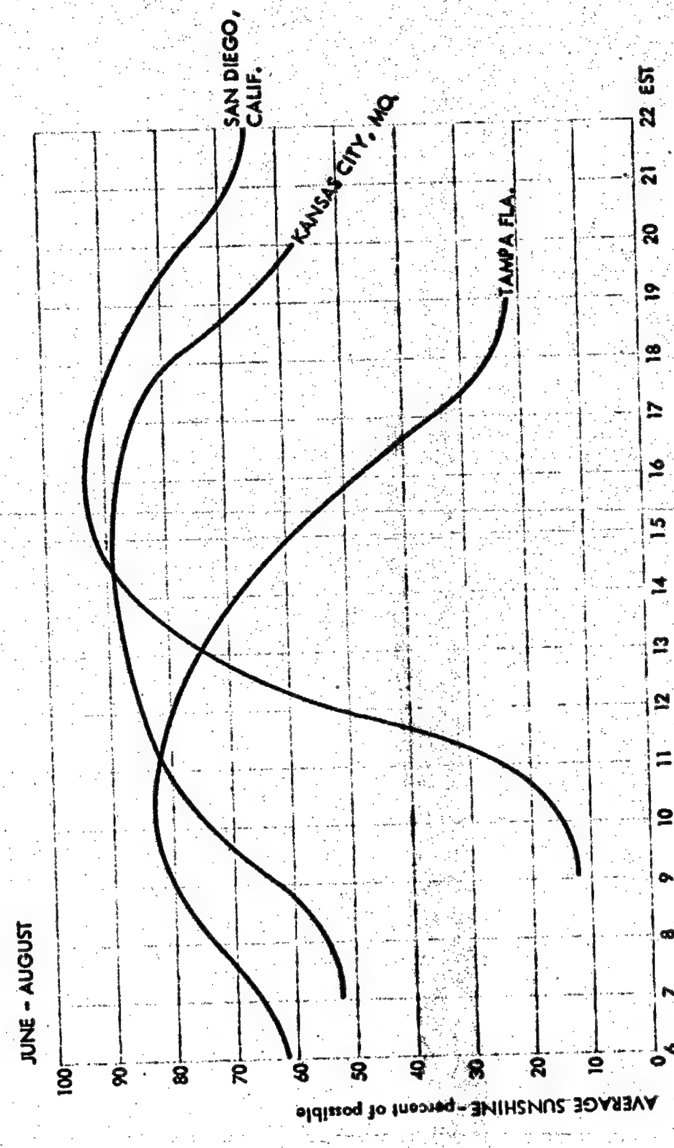
The values of ignition radius were approximated from the following equations:

Optimal Receiver: $$Q = \frac{1.04\ WT}{h^2 + d^2}$$

Horizontal Receiver: $$Q = \frac{1.04\ WTh}{(h^2 + d^2)^{3/2}}$$

where, as before, Q is the incident radiation in calories/cm^2, T is the transmission factor, W is the yield in kilotons, h is the burst height in miles, and d is the distance from ground zero, or ignition radius, in miles. By substituting the hourly values of R, from Hourly Solar Radiation Data (1962), for T in these equations, time histories of ignition radius, d, are obtained. Because the actual variation of R with receiver orientation is not known, the results are only approximate. This is particularly true for the optimal receiver and for atmospheric conditions for which R is small since here much of the radiation is diffuse and thus less sensitive to receiver orientation. Further approximations

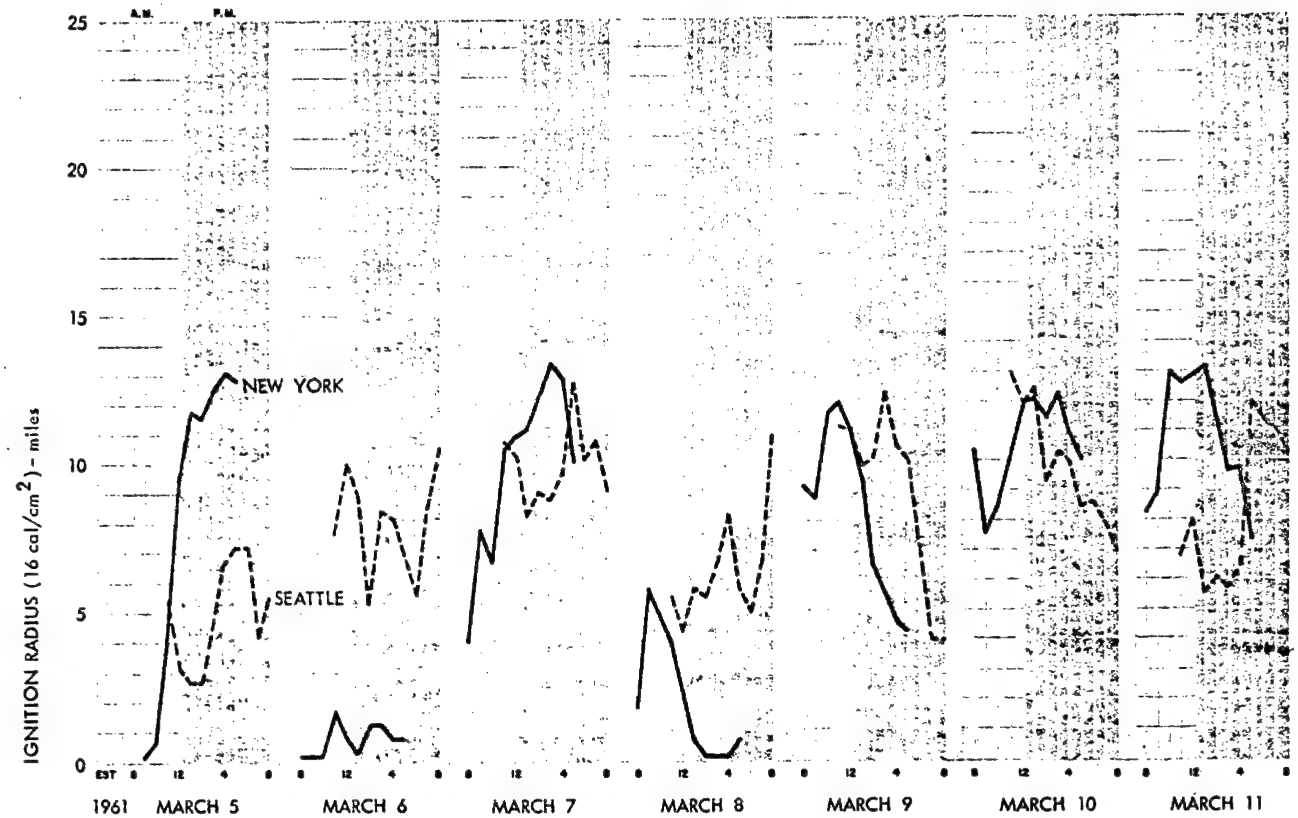
Figure C-8
AVERAGE SUNSHINE VS HOUR
(simultaneous readings)



SOURCE: Visher (1954)

Figure C-9

VARIATION OF IGNITION RADIUS WITH TIME FOR A BURST ABOVE CLOUDS—HORIZONTAL RECEIVER (week of March 5 - March 11, 1961)

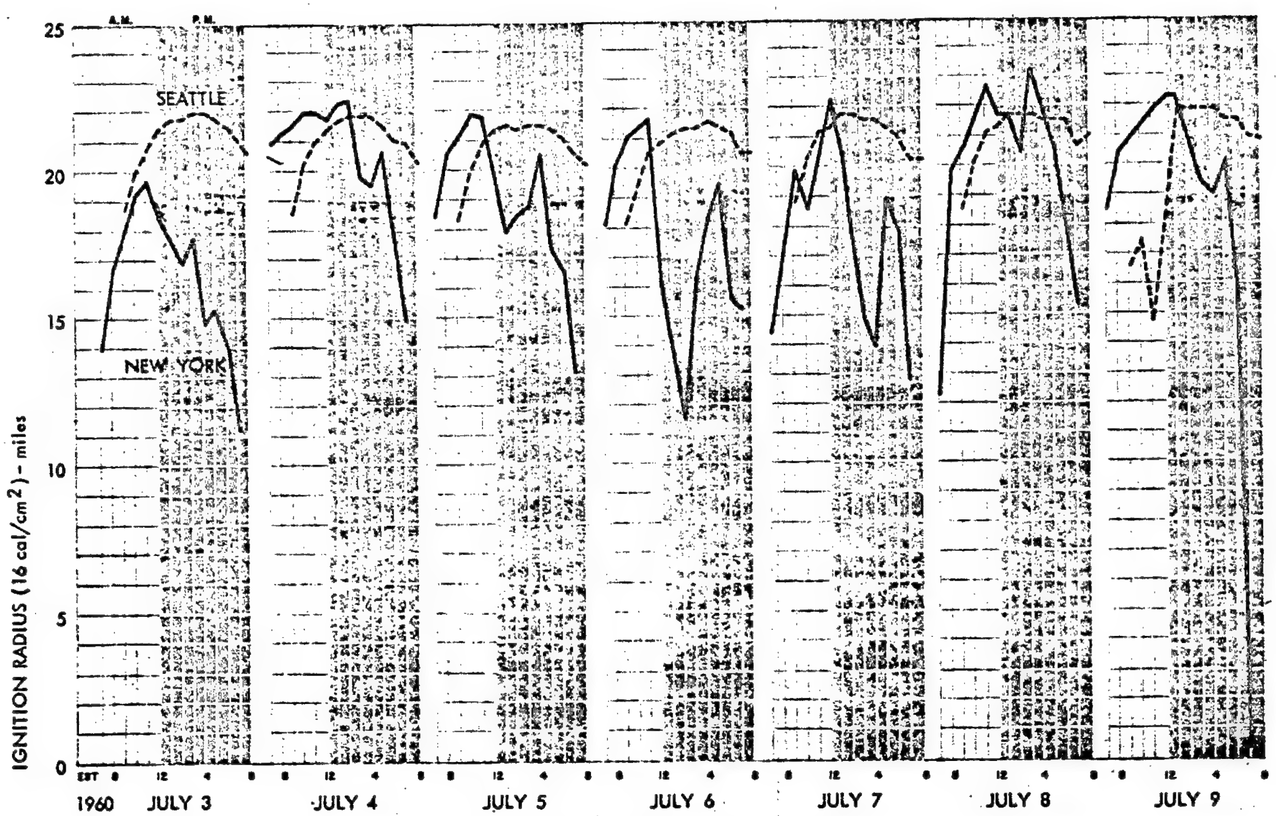


NOTE: Yield = 10 mt (Based on ignition requirements of Miller (1962) and Glasstone (1962)
35 mt (Based on ignition requirements of Martin (1959)
Burst height = 30,000 feet

SOURCES: Hourly Solar Radiation Data (1962) and Stanford Research Institute

Figure C-10

VARIATION OF IGNITION RADIUS WITH TIME FOR A BURST ABOVE CLOUDS—OPTIMAL RECEIVER (week of July 3 - July 9, 1960)



NOTE: Yield = 10 mt (Based on ignition requirements of Miller (1962) and Glasstone (1962)
35 mt (Based on ignition requirements of Martin (1959)
Burst height = 30,000 feet

SOURCES: Hourly Solar Radiation Data (1962) and Stanford Research Institute

in both cases are the assumptions that the burst is above the clouds and that all the measured attenuation is caused by the atmosphere below the burst altitude.

Height of cloud top is not a regularly recorded observable; and, in fact, the height of the cloud base in multiple layer cases is unobservable. As mentioned in Passell (1963), this lack of data could be alleviated to some extent by the use of existing radiosonde humidity records to indicate height of cloud tops. Despite these shortcomings, it is felt that Figures C-9 and C-10 give a good indication of the possible short term variations in ignition radius. These variations would probably be even greater for bursts at lower altitudes--in and below the cloud layers--where conditions are more variable.

The assumption of a 30,000-foot burst being above the clouds deserves further investigation. Solomon (1961) gives estimates of the altitudes above which there is a given probability of less than 1/10 cloud cover. For example, in January, an 80 percent probability exists that there is less than one-tenth cloud cover above about 25,000 feet for the extreme northern United States and above 33,000 feet for the southern United States. For the other months given, the corresponding ranges of altitude are: April, 30,000 to 42,000 feet; July, 30,000 to 46,000 feet; and October, 10,000 to 39,000 feet. Since these figures are for one-tenth cloud cover and since the albedo of the usual cirrus type of cloud at these altitudes is not very great, whether the 30,000-foot burst is above or below the clouds should make no great difference (see Figures B-16 and B-19). However, as the burst height decreases to more realistic values for 10-mt yields and below, there is increasing probability that it will be in or below the clouds, and much more complicated computations will be involved.

While the curves of Figures C-9 and C-10 indicate large variations of ignition radius for individual cities, the total variation on a nationwide basis may be much less. One way to investigate this would be to sum the ignition area or the number of people within the ignition area of all (large) cities. This could be done as a function of time by the use of radiation data similar to that in the Hourly Solar Radiation Data for all cities of interest for which data are available. While the amount of input data would be quite large, the computations would be relatively simple and straightforward. Such a computation, carried out for a year's data, would give a good indication of the mean and extreme values of nationwide ignition values. This would apply only to a daytime and above-the-clouds strike. To determine the variation of attacks under other conditions requires the analysis of much additional data.

Until this decade almost all of the weather data available were obtained from surface stations augmented by balloon soundings and scattered aircraft reports. While producing an enormous amount of data by any numerical standards, the coverage has never been adequate for many areas of the world, particularly those bounded on the west by large stretches of ocean in which there is little shipping activity. Even in the case of the United States, there are insufficient surface observations in the North Pacific to allow adequate prediction of U.S. cloud cover on the scale required for nuclear fire prediction.

All of this is changing, however, with the advent of the Tiros weather satellites. The television pictures that have been taken of cloud (and snow) cover, together with the radiation measurements, have added enormously to the range and significance of available weather and, ultimately, climatological information. In fact, many areas of meteorology--both research and operational--are undergoing a rapid evolution, if not a revolution, as a consequence of the satellite data. This evolution will be further accelerated as data gathering and transmission techniques improve in terms of resolution and orientation, as data analysis techniques are speeded up, and as the newer earth-oriented polar orbiting Nimbus satellite becomes operational.

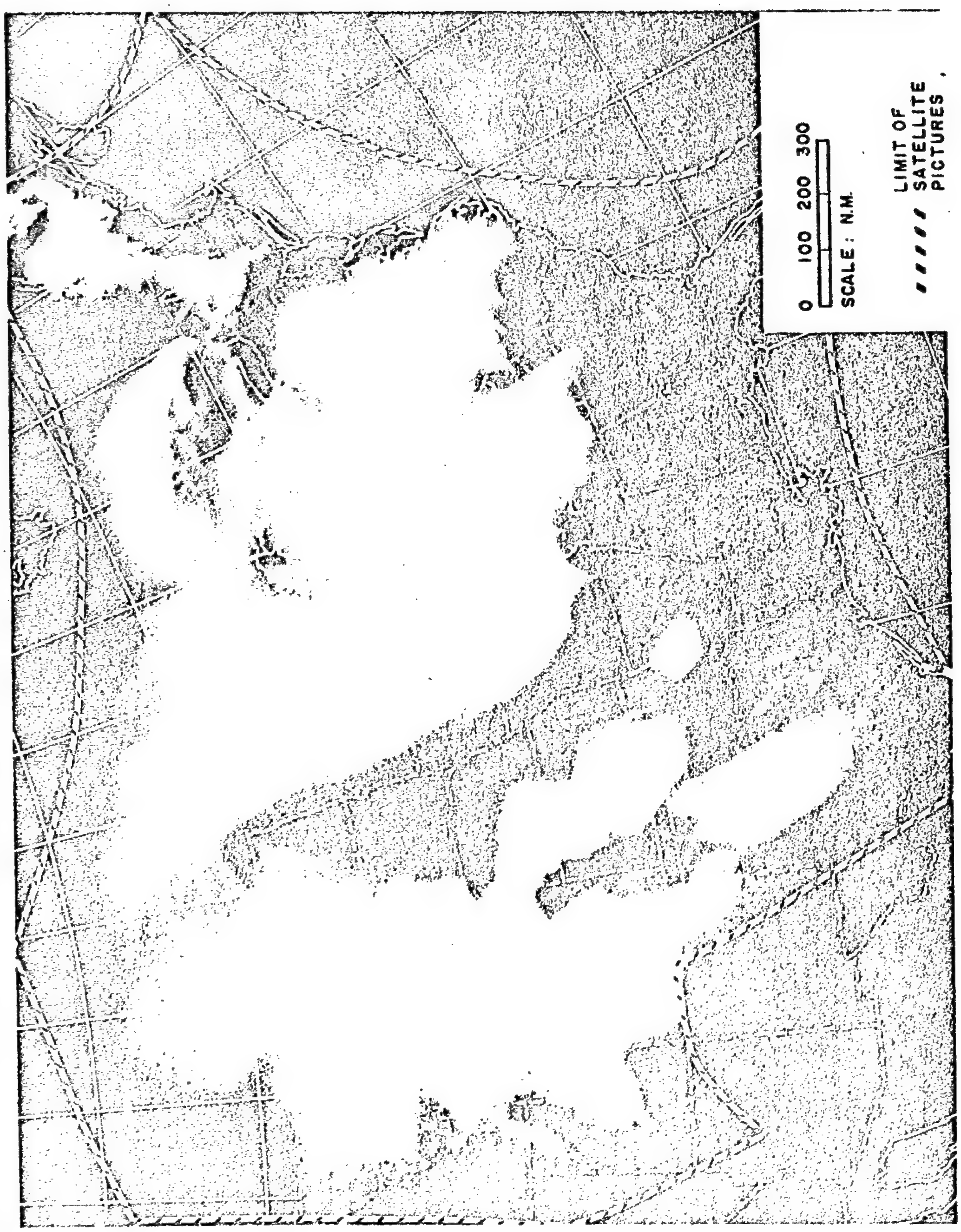
Because of the newness of the satellite data, the bulk of the effort to date has involved a search for new techniques of analysis and presentation--see Figure C-11--and for correlations of satellite pictures and radiation measurements with existing surface observations, including radar, and upper-air soundings; see, for example, Nagle and Blackmer (1962). Already, however, the following facts pertaining to nuclear attack fire research are becoming clear.

1. The prediction of the motion of large-scale clear areas for periods of 24 to 48 hours for operational purposes appears entirely feasible. This has been indicated in a study, Serebreny (1962), of Tiros pictures of cloud patterns in the North Pacific. This included, among other phenomena, the easterly motion of a large clear area (approximately 250,000 square miles), the existence of which would probably have been entirely missed until too late for incorporation into attack plans if the usual extrapolation of scattered surface reports in this area had been used. This type of predictive capability would be particularly important in the event that an attacker decided to tailor his potential attack to weather conditions or the United States decided to implement an operational fire damage assessment system.

2. The broad-scale coverage of cloud patterns, while it does not give cloud height and other detailed information, provides information

Figure C-11

COMPOSITE REPRESENTATION OF CLOUDS OBSERVED BY TIROS I



Orbits 0818, 0819, and 0820 over continental U S on afternoon of 27 May 1960, 2000 GMT to 2300 GMT (approx)

SOURCE: Nagle and Blackmer (1962)

concerning many potential target areas which would not otherwise be included in regular weather observations. For these cases and possibly for many others, Tiros pictures may be the best way to develop an approximate cloud climatology. Certainly, it offers the best long term potential for simultaneous nationwide (daytime) cloud coverage. However, the time required to provide meaningful averages and extremes is not known.

4. The use of Tiros pictures to determine the extent of snow cover in many areas also appears feasible and may be helpful in determining the frequency and importance of Case IV weather conditions (snow cover); see Tarble (1962).

5. The correlation of satellite measurements of radiation with the corresponding cloud pictures should lead to simplified techniques for obtaining albedo for the entire local cloud configuration. This would be of immediate use in determining the amount of radiation which will reach the surface from high altitude and above-the-atmosphere bursts. While this particular correlation has not yet been made in detail, initial steps have been taken in the comparison of satellite radiation with cloud patterns--Rasool (1962) and Nordberg, et al. (1962)--and other conditions--Winston and Rao (1962)--for various areas of the globe.

To summarize the data and techniques available, sufficient radiation data exist to establish an approximate transmission factor or ignition radius climatology for a daytime above-the-cloud attack. There are, however, insufficient computational results of transmission factors for bursts within or below clouds, for nighttime attacks, and for various receiver orientations, as well as insufficient weather data to describe these cases in detail. The situation could be improved somewhat by available techniques, including the use of radiosonde data to determine cloud heights; the correlation of radiation measurements with other weather observables to provide estimates of transmissivity for above-the-cloud nighttime attacks, Passell (1963); and extension of existing computational programs. In addition, the data from weather satellites will afford improved results and a wider area of applicability.

Effect of Weather on the Target System Vulnerability

Effect of Weather on Materials

The vulnerability of materials to ignition and fire spread is predominantly weather dependent because of the moisture content of the materials. For a given temperature, as the relative humidity of the

surrounding air increases to a given value, the moisture content of a material will be less than if the relative humidity decreases to that value. In Figure C-12 are sketched three curves relating the moisture content of woody materials to the humidity of the surrounding air at a temperature of 25°C; see Thermal Properties of Forest Fuels (1952). The lower curve shows the relationship when relative humidity is increased at a constant temperature and moisture content increases (adsorption). The upper curve shows values obtained when relative humidity is lowered at constant temperature and moisture content decreases (desorption). The intermediate curve shows a laboratory method called the oscillating vapor pressure method which combines desorption and adsorption. This curve defines the equilibrium moisture content, which is most frequently used in the discussion of materials. An approximation to the moisture content-humidity relation of woody materials is also shown on the graph (Henry's Law).

Figure C-13 shows the relationship of relative humidity, equilibrium moisture content, and partial vapor pressure for different temperatures. It should be pointed out, however, that in problems related to burning of materials, the heating is actually a desorption process; hence the desorption moisture content relationships to humidity are the most significant. The theory of moisture content of forest fuels, the relation of moisture content to specific heat capacity of the fuels, and other thermal properties of forest fuel are explored in some detail in Thermal Properties of Forest Fuels (1952). Graphs are given for the amount of heat required to decrease the moisture content of a material by 1 percent at a given temperature. Thermal Conductivity of Some Common Forest Fuels (1952) also contains much information of the thermal properties of forest fuels.

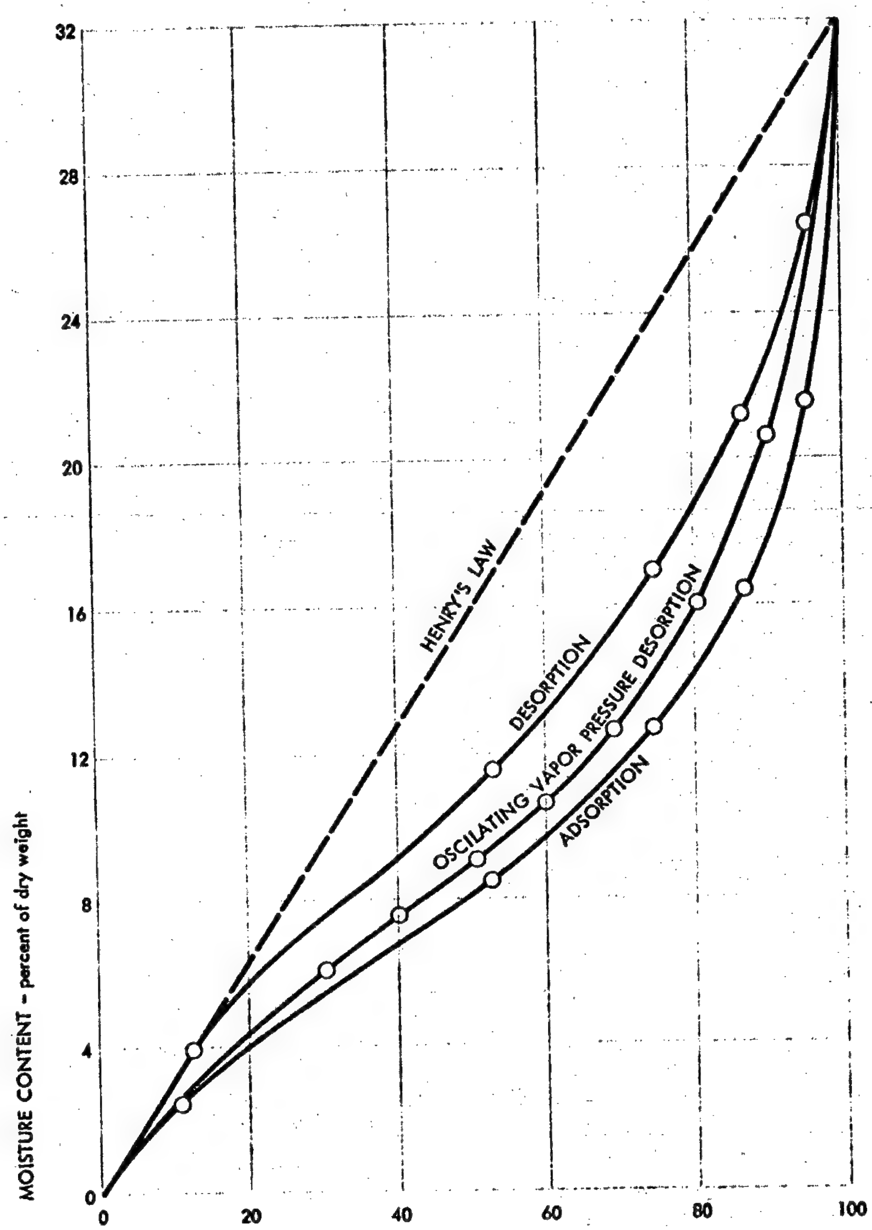
Figure C-14 illustrates that the moisture content is practically independent of the kind of wood used in the interior woodwork of a house. For kindling fuels which are not necessarily woody materials, Table B-VI lists the equilibrium moisture contents. Data for a few additional materials are presented in Table C-IV. For fine fuels within structures, Table A-III and the related discussion on page A-47 describe a method for estimating equilibrium moisture from external temperature and humidity readings. See also Pirsko and Fons (1956).

Effect of Weather on the Vulnerability of Structures

The moisture content of heavy fuels in dwellings has been studied in meticulous detail in Peck (1932). Figure A-30 has shown one example of the results. Figure C-15 shows that the moisture content of the

Figure C-12

MOISTURE CONTENT AS A FUNCTION OF RELATIVE HUMIDITY

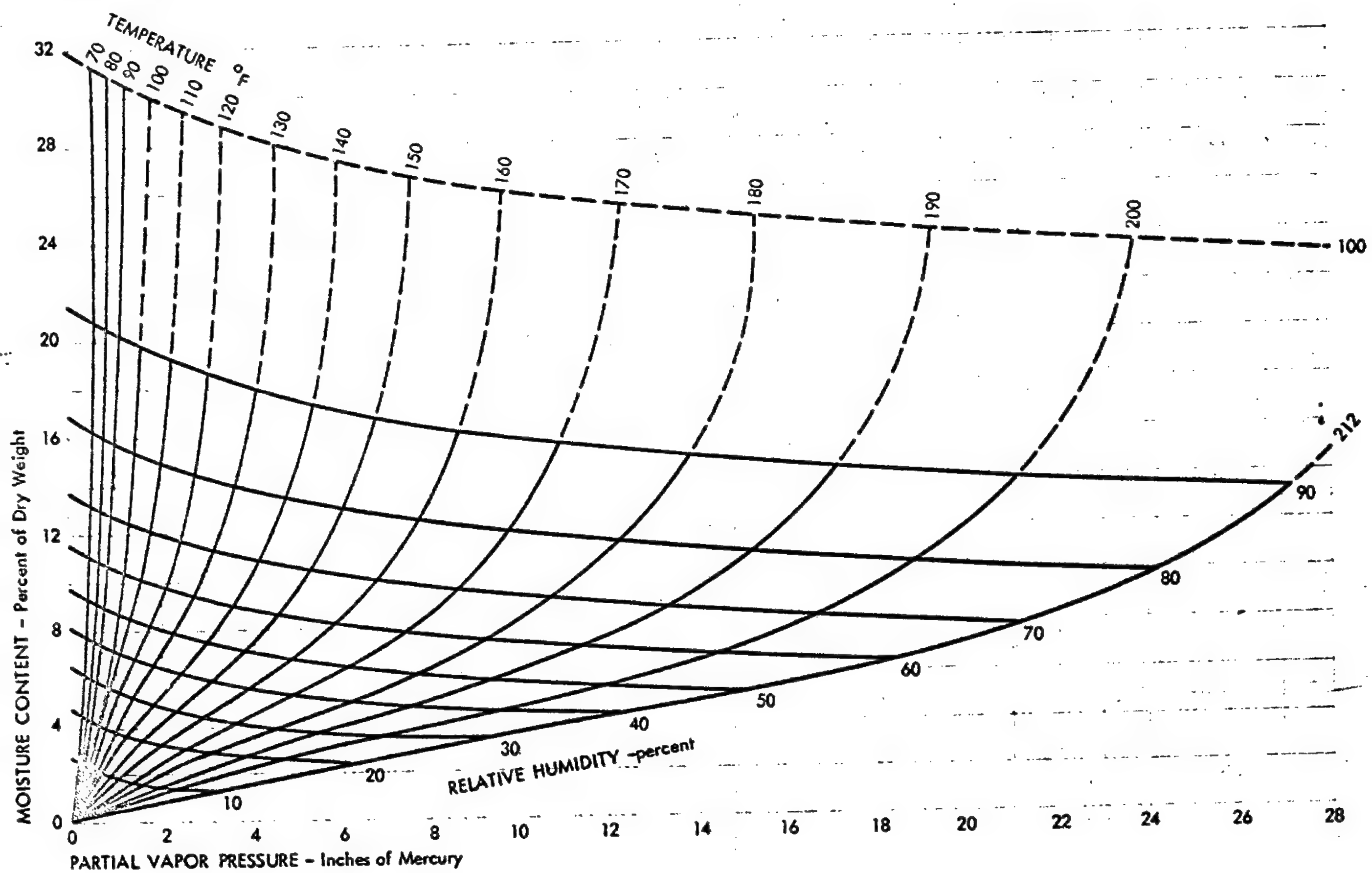


RELATIVE HUMIDITY - percent

SOURCE: Byram et al. (1952)

Figure C-13

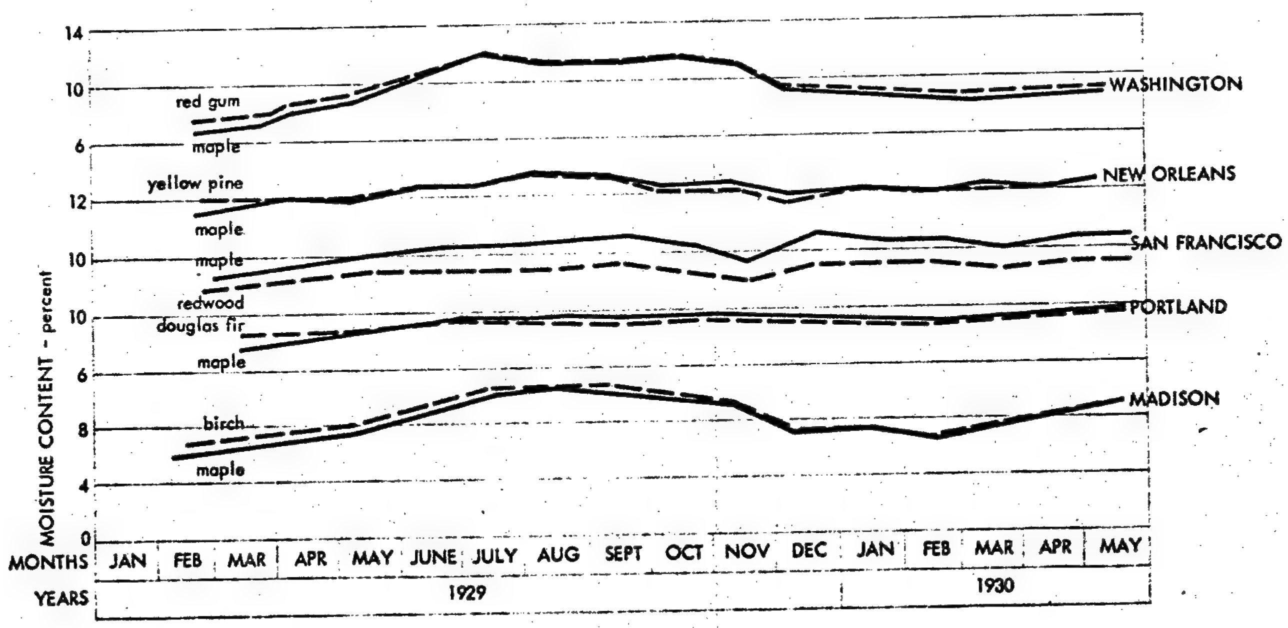
RELATIONSHIP BETWEEN EQUILIBRIUM MOISTURE CONTENT, RELATIVE HUMIDITY, TEMPERATURE, AND PARTIAL VAPOR PRESSURE



SOURCE: Byram et al. (1952)

Figure C-14

AVERAGE MOISTURE CONTENT OF SHELLACKED MAPLE BLOCKS OF DIFFERENT SPECIES IN THE "LIVING" PART OF HOUSES STUDIED IN SIX WIDELY SEPARATED CITIES



SOURCE: Peck (1932)

Table C-IV

EQUILIBRIUM MOISTURE CONTENT OF SOME FINE MATERIALS
AT SURROUNDING AIR TEMPERATURE OF 75°F
(Percent)

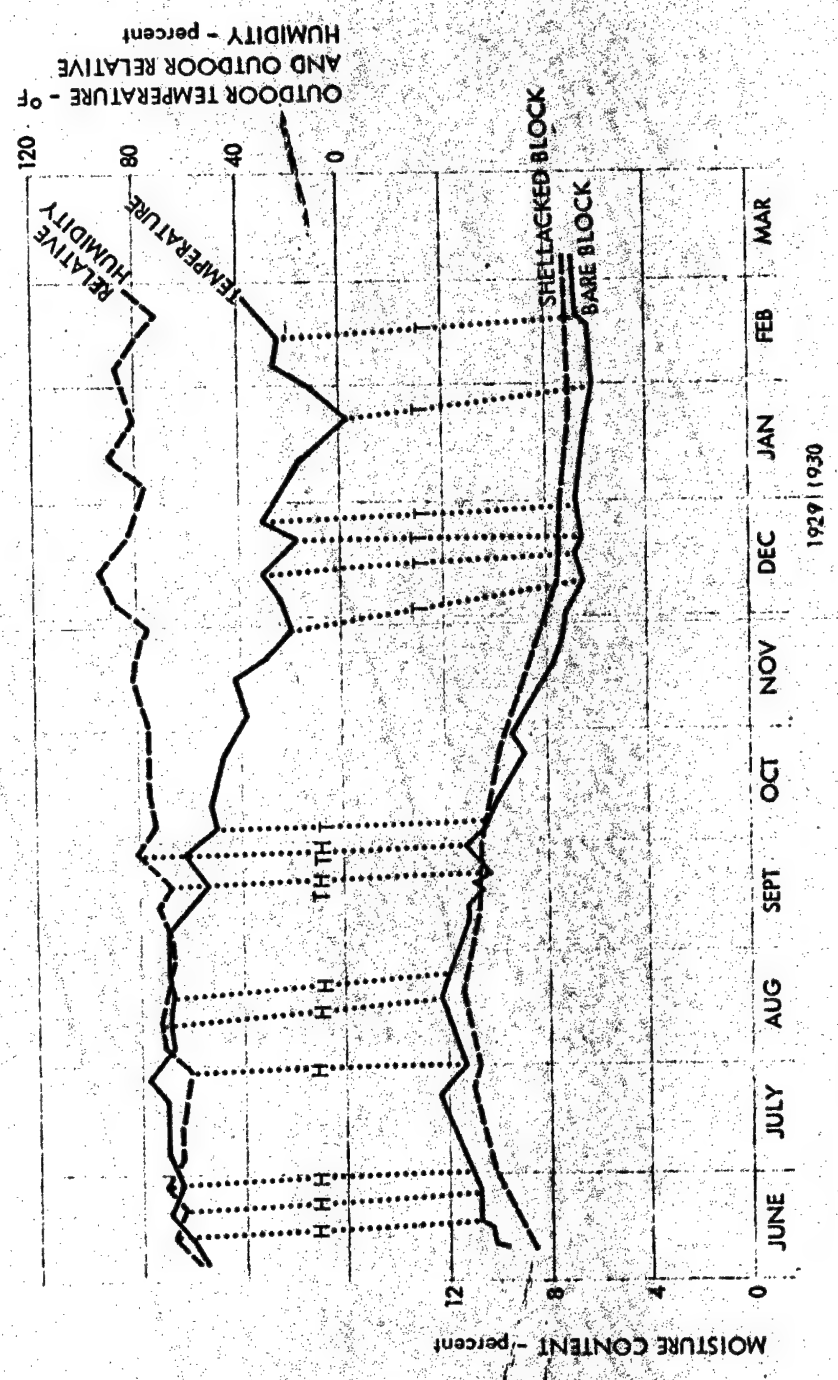
Material	Equilibrium Moisture Content at Relative Humidity of:								
	10%	20%	30%	40%	50%	60%	70%	80%	90%
Cotton cloth	2.6%	3.7%	4.4%	5.2%	5.9%	6.8%	8.1%	10.0%	14.3%
Wool skein	4.7	7.0	8.9	10.8	12.8	14.9	17.2	19.9	23.4
Newsprint	2.1	3.2	4.0	4.7	5.3	6.1	7.2	8.7	10.6
Writing paper	3.0	4.2	5.2	6.2	7.2	8.3	9.9	11.9	14.2
Kraft wrapping paper	3.2	4.6	5.7	6.6	7.6	8.9	10.5	12.6	14.9
Average[a]	3.1	4.5	5.6	6.7	7.8	9.0	10.6	12.6	15.5

a. Average almost identical to kraft wrapping paper.

Source: Pirsko and Fons (1956).

Figure C-15

AVERAGE MOISTER CONTENT OF SHELLACKED MAPLE BLOCKS REPRESENTING THE INTERIOR WOODWORK IN VARIOUS PARTS OF HOUSES



SOURCE: Peck (1932)

interior woodwork in general follows the outdoor temperature more closely than it does the humidity. Figure C-16 shows that wood which has not been protected by a finish is much more responsive to humidity changes than unfinished wood. This is probably a major cause for the breakdown of the cellular structure of unpainted wood and the general effects of weathering.

Effect of Weather on Countermeasures

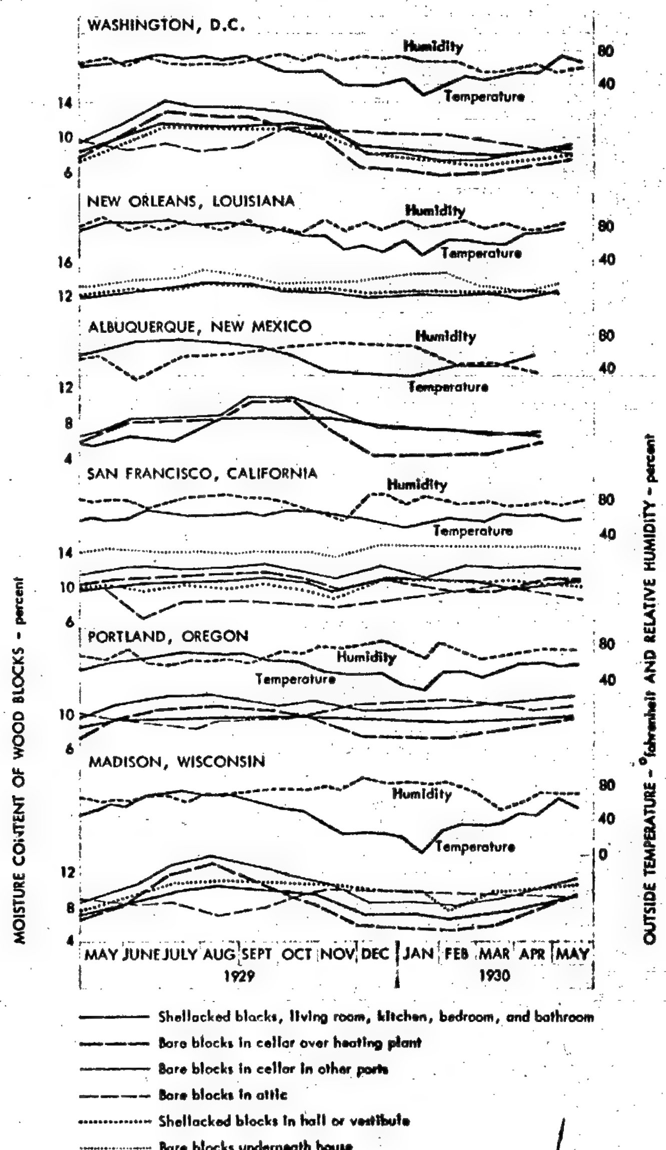
Weather plays a dominant role in the feasibility of employing smoke generators to protect large areas from the thermal flash of a nuclear detonation. In Duckworth, et al. (1953), a study is made of the meteorological feasibility of such a tactic. It is assumed that a weapon is detonated between 1,200 and 2,000 feet altitude over a city. Under the additional assumptions that (1) the smoke cloud is uniformly distributed between the ground and some higher altitude and (2) attenuation of thermal radiation results from scattering and not absorption, it is shown that some protection from the cloud will result if the height of the cloud is not greater than twice the detonation altitude. Of course, maximum protection will be obtained if all the smoke lies beneath the detonation point.

With the criterion established that the smoke layer must not be deeper than 2,400 to 4,000 feet, it is argued that either an inversion layer below the critical heights or a wind strong enough to move the smoke across the city before it reaches the 2,400 to 4,000 foot level would be adequate for protection. Nighttime conditions are found most suitable since an inversion layer is very common after dark; daytime inversions are less frequent. Neutral conditions limit the extent of vertical diffusion to approximately one-tenth the distance traveled by the cloud. If natural clouds exist, complications arise. If the natural clouds are above the smoke and detonation point, the radiation will be reflected downward and the smoke will help shield the target. If the natural clouds are below the detonation, they will help absorb the energy.

With the requirements established for inversion heights and wind speeds, statistical data on these parameters are collected for four cities in Duckworth, et al. (1953). The results appeared to be encouraging.

Figure C-16

AVERAGE MOISTURE CONTENT OF MAPLE BLOCKS ON THE INNER WALL OF THE LIVING ROOM OF A HOUSE AT MADISON, WISCONSIN; CORRESPONDING WEEKLY AVERAGE OUTDOOR TEMPERATURE AND RELATIVE HUMIDITY



SOURCE: Peck (1932)

Effect of Weather on Fire Processes

Ignition of fine fuels by the thermal flash of nuclear weapons has been discussed in detail earlier in this paper. Weather affects the susceptibility of materials to flash ignition predominantly by changing the moisture content of the fuel. The moisture content was found to be a function of the humidity for exterior fine fuels and temperature and humidity for interior fine fuels.

Once a fire has started, further development depends on spread by direct radiation, conduction, convection from hot gases, or transport of firebrands. For ignition of these processes, weather factors other than just humidity are important. In fact, for fine fuels, moisture is quickly driven out by heating and has little effect in retarding fire spread. Since ignitions occur when a fuel reaches a critical temperature, fuels that are preheated by sunlight or high air temperatures will ignite more quickly than cool materials. In addition, winds will increase the rate of fire spread not only by supplying fresh oxygen to the flames, but also by bending the convection column of hot gases nearer the unburned fuels and thereby increasing their initial temperatures. Of course, winds may also blow the flames away from fresh fuel and slow down the ignition process. High humidity, together with an inversion at the time of inception of a fire, retards the formation of a pillar of air currents, and a smoky and slow-burning fire will result. Winds are responsible for the transport of burning embers, which seems to be the dominating fire propagating mechanism for high intensity forest (and probably urban) fires; Davis (1959).

Rain will not only wet down fuels in the path of a fire but will cool convection currents of hot gases and extinguish many of the flying embers. However, in wartime experience, damage averaged only 20 percent less during rain than under favorable conditions; see Bond (1946). Snow will probably have even less effect since it does not tend to wet vertical surfaces, such as sides of structures.

For fires started within buildings by the thermal flash, the effect of moisture content on ignition and rate of fire spread is most pronounced on structural members two inches or more in thickness and least pronounced with light sections such as 1/4-inch paneling; see Bomb Damage Analysis (1949). The finer fuels are more quickly dried by heat of the fire. When the moisture content of larger members is greater than about 15 to 16 percent, the heavier members are difficult to ignite and incapable of propagating a vigorous fire even if ignited. Below 12 percent moisture content, wood of any thickness is quite easily ignited and propagation of fire is quite rapid. The relationship between moisture

content and humidity has been found to be surprisingly constant for all species of wood. (See Bomb Damage Analysis (1949) and Figure C-12 of this report.)

From wartime experience with incendiary bombs, it was found that for the initial stages of a fire, the average humidity for a three-week period determines the susceptibility of a structure to fire. An average relative humidity above 70 percent in winter and 75 percent in summer will produce an equilibrium moisture content greater than 15 percent and will appreciably increase the difficulty of initiating a vigorous fire. Even in this case, however, if a sufficient quantity of combustible material--in the form of lightweight panels or in any other form characterized by large surfaces per unit volume--is present, the fire can overcome the retarding effect of moisture in heavier members and cause extensive destruction; see Bomb Damage Analysis (1949).

Pirsko and Fons (1956), in a study on fire starts within buildings, demonstrated that humidity and temperature were the only weather variables which showed any correlation with the average number of fires started per day. Of course, fire starts would only be a crude index of the seriousness of fires originating from nuclear weapons radiation.

If windows are open or are broken, as would probably be the case after a low altitude enemy attack, or if a wall collapses, only then will winds influence the progress of fires inside buildings. For example, in Salzburg, et al. a model is developed which predicts that the burning rate (lb/min) of a fire in a single-level structure or multiple-level structure with each level isolated as to ventilation is directly proportional to the wind velocity. Equations are also given for the burning rate of other type structures. Hamada (1952) has found that for flames on a (flat) roof, the tangent of the angle between the flame and the horizon is inversely proportional to the square of the velocity of the wind. This and other studies of this type appear to be important in the evaluation of fire spread by radiation from burning buildings.

Studies of the results of incendiary attacks during the war give some indication of the effect of weather on the spread of fires between structures in urban areas. For example, from Bomb Damage Analysis (1949):

> "It may be said that wind is the greatest potentially favorable factor in promoting a conflagration and the production of really catastrophic damage. In fact, even when the favorable influence of all other factors is at the maximum, it is still likely that fires will be controlled by determined defensive measures unless the wind velocity is greater than 15 miles

an hour. As the wind velocity rises from 15 to 30 miles an hour, the rate of fire propagation from building to building increases enormously and at the latter figure even a relatively minor blaze, involving a group of but two or three dwellings, may constitute a serious threat to the whole of the down-wind area."

In the case of mass fires which might develop from a nuclear attack, two possible phenomena may occur--the conflagration or the firestorm. The conflagration is a term generally applied to a fire extending over a considerable area and destroying numbers of buildings. It is a moving fire which depends predominantly on natural pre-existing winds to bring the convection column of hot gases down to unburned fuel in the path (of the fire), thereby spreading at an exceedingly rapid rate. An analysis of the most destructive U.S. and Canadian conflagrations indicates that in 58 percent of the cases, wind was second to wood shingles as the most important factor; see Fire Protection Handbook (1962). Because of its speed, it does not create as complete destruction as does a firestorm in any given area; however, it may cover much more territory. A firestorm is a mass fire which may develop when ground winds are light or absent. If fires are burning simultaneously over a large enough area, induced winds will rush toward the center of the fire, creating an extremely hot, destructive, but rather stationary mass fire. In this case, the relationship between fire and weather works in two directions; not only do the meteorological elements influence the development of fires, but firestorms create strong, hot winds and, in some cases, rain will fall.

The firestorm-induced winds in Hamburg, for example, reached a velocity of 53 km/hr; see Brown (1962). About 12 hours after the firestorm, upper air readings showed that convection broke through the cold ground layer of air and a cloud formed as the warm air reached the cold upper air. The cloud height reached 20,000 feet and remained over the city for more than 24 hours; see Bond (1946). In the Leipzig firestorm, there was evidence that winds greater than 75 mph were created by the storm; Bond (1955). In Hiroshima, the induced winds were 30-40 mph two to three hours after the explosion; Fire Effects of Bombing Attacks (1959). Experimental forest fire tests in the United States have produced 54 km/hr induced winds; Ignition of Fires . . . (1962). Conflagrations and firestorms in both peacetime and wartime have been described in many papers, to which the reader is referred for further details; see Fire Effects of Bombing Attacks (1959), Bond (1946), Earp (1953), and others.

In Japan, peacetime conflagrations have been numerous and were documented as early as 1434 when more than 10,000 homes were destroyed by fire in a couple of days. Based on these statistics, the Japanese have

developed many models and rules-of-thumb for estimating fire risk for insurance purposes. The applicability of these results to the problem of fire spreadin U.S. urban communities and the reliability of the statistical analyses are unknown. The studies are important, however, for the identification of critical parameters and methods of approach.

Yoshino (1958) has studied the shifting of the fire in several urban conflagrations. Figure C-17 shows the fire spread rates of two conflagrations. It is seen that the velocity of the fire front immediately after the outbreak is exceedingly great. After the first hour, the front slows down but spreads out nearly radially in all directions and decelerates according to a fairly regular pattern.

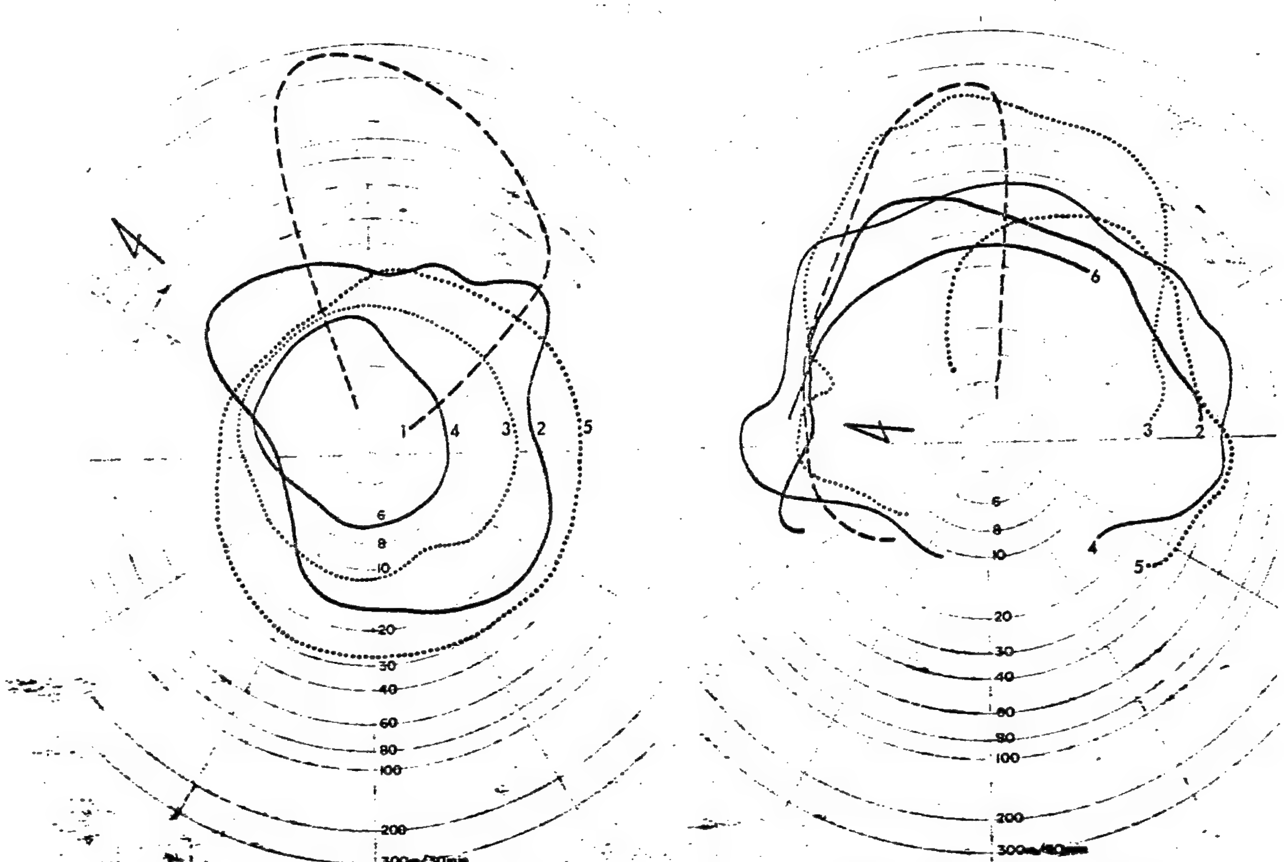
Hishida (1952) has also given considerable data on the influence of wind on the fire spread rates in urban conflagrations. Table C-V shows the mean velocity of the fire front in the leeward, windward, and downwind directions. Table C-VI gives the time required for fire to spread between buildings and the distances required for firebreaks, as a function of wind velocity, the width of the building on fire, a, the distance between the building on fire and the next building, d, and the direction of the wind. Table C-VII shows the perimeter and the area of the oval-shaped burned region as a function of wind speed and the time from the start of the fire. The perimeter, of course, is of greatest importance to firefighters; the area is important for estimating total damage. In Table C-VIII is shown the relation between the firebreak width required to stop the fire (marginal distance), the distance burned, the time from the start of fire, and the wind direction and wind velocity. These data were derived for ordinary wooden construction. For "very humble wooden construction," the firebreak widths should be multiplied by 10/7.

In Table C-IX, Hishida gives the burn-out area of a fire when public fire defense fails and the fire burns itself out. It is assumed that the fire has burned for 50 minutes and that there is no change of wind. The percentage of the total area which is covered by roads is an independent variable as is the percentage of the remaining area (total area minus road area) which is covered by buildings. Hishida notes that the causes for the self-extinguishment of a fire are unknown but that they are undoubtedly related to meteorological conditions, especially a change of of wind direction and velocity.*

* In forest fire experience in the United States, the self-extinguishment of the fires has often been attributed to meteorological conditions. In Chandler (1960), for example, the final stages of the fire behavior were influenced strongly by the invasion and recession of marine air.

Figure C-17

FIRE FRONT MOVEMENT: NIIGATA CITY AND NOSHIRO CITY



NIIGATA CITY, OCT. 1, 1955

NOSHIRO CITY, MARCH 20 - 21, 1956

NOTE: Numbers indicate hours in order; i.e. first one hour = 1, second one hour = 2, etc.

SOURCE: Yoshino (1958)

Table C-V

MEAN VELOCITY (M/MIN) FOR GIVEN LAPSE OF TIME

Time (min)	Direction of Wind	Wind Velocity 1.5	5.0	12.0	20.0
5	V1	0.30	0.40	0.60	1.20
	V2	0.20	0.20	0.30	0.40
	V3	0.25	0.25	0.35	0.50
10	V1	0.80	1.20	2.40	4.50
	V2	0.50	0.50	0.70	1.00
	V3	0.60	0.70	1.00	1.50
15	V1	1.00	1.60	3.10	6.40
	V2	0.50	0.60	0.90	1.40
	V3	0.70	0.90	1.30	2.00
20	V1	1.20	1.90	3.70	7.70
	V2	0.50	0.60	1.10	1.60
	V3	0.80	1.10	1.50	2.40
30	V1	1.40	2.30	4.60	9.60
	V2	0.60	0.70	1.30	1.90
	V3	0.90	1.20	1.80	3.00
60	V1	1.50	2.70	6.30	13.20
	V2	0.70	0.80	1.40	2.30
	V3	1.00	1.30	2.10	3.90

Note: V1 = leeward.
V2 = windward.
V3 = windside.

Source: Hishida (1952).

Table C-VI

RESULTS OF STATISTICAL ANALYSIS OF CONFLAGRATION BEHAVIOR

Direction of Wind	Section of Time from the Fire Outbreak (min)	Time Necessary for Spread to Neighboring House (both one story) (min)	Marginal Distance of Open Space Not to Spread to Neighboring House
Leeward	0-10	$t1 - \frac{3 + \frac{3}{8}a + 8\frac{d}{D}}{1 + 0,1V + 0.007V2}$	$D = 5 + \frac{V}{2}$
	10-30	$t2 = t1/1.2$	1.5D
	30-60	$t3 = t2/1.4$	3.0D
	60-	$t4 = t3/1.6$	5.0D
Windward		$t' = \frac{3 + \frac{3}{8}a + 8\frac{d}{D'}}{1 + 0.005V2}$	$D' = 5 + \frac{V}{5}$
Windside		$t'' = \frac{3 + \frac{3}{8}a + 8\frac{d}{D''}}{1 + 0.005V2}$	$D'' = 5 + \frac{V}{4}$

Note: V = wind vel m/sec.
a = width of building on fire (meters).
d = distance between "a" and next building.

Source: Hishida (1952).

Table C-VII

AREA AND PERIMETER OF A CONFLAGRATION

V m/sec		t min 5	10	15	20	30
1.5	perimeter (m)	8	30	55	85	150
	area (m^2)	6	115	380	830	2,450
5.0	perimeter	11	50	100	150	270
	area	8	200	760	1,800	5,550
12.0	perimeter	14	80	170	260	440
	area	15	610	2,200	5,700	18,800
20.0	perimeter	19	140	470		
	area	30	1,630	7,600		

Source: Hishida (1952).

Table C-VIII

FIREBREAK REQUIREMENTS AND THEIR RELATION TO DISTANCE BURNED[a]

Time (min)	Direction of Wind	Wind Velocity (m/sec) 1.5 Marginal Distance	1.5 Distance Burned	5.0 Marginal Distance	5.0 Distance Burned	12.0 Marginal Distance	12.0 Distance Burned	20.0 Marginal Distance	20.0 Distance Burned
5	V1	5.0	1.5	5.0	2.0	5.0	3.0	8.4	6.0
	V2	5.0	1.0	5.0	1.0	5.0	1.5	5.0	2.0
	V3	5.0	0.8	5.0	1.3	5.0	1.8	5.0	2.5
10	V1	5.6	8.0	8.4	12.0	16.8	24.0	31.5	45.0
	V2	5.0	5.0	5.0	5.0	5.0	7.0	7.0	10.0
	V3	5.0	6.0	5.0	7.0	7.0	10.0	10.5	15.0
15	V1	7.0	15.0	11.2	2.4	21.7	46.5	44.8	96.0
	V2	5.0	7.5	5.0	9.0	6.3	13.5	9.8	21.
	V3	5.0	10.5	6.3	13.5	9.1	19.5	14.0	30.
20	V1	8.4	24.0	13.3	3.8	25.9	74.0	53.9	154.
	V2	5.0	10.	5.0	12.	7.7	22.	11.2	32.
	V3	5.6	16.	7.7	22.	10.5	30.	16.8	48.
30	V1	9.8	42.	16.1	69.	32.2	138.	67.2	288.
	V2	5.0	18.	5.0	21.	9.1	39.	13.3	57.
	V3	6.3	27.	8.4	36.	12.6	54.	21.0	90.
60	V1	10.5	90.	18.9	162.	44.1	378.	92.4	792.
	V2	5.0	42.	5.6	48.	9.8	84.	16.1	138.
	V3	7.0	60.	9.1	78.	14.7	126.	23.7	234.

Note: Marginal distance = meters. V1 = leeward, V2 = windward, V3 = windside.

a. Applies to ordinary wooden construction.

Source: Hishida (1952).

UNCLASSIFIED

Table C-IX

ASSUMED AREA OF FLOOR OF BURN
WHEN PUBLIC FIRE DEFENSE FAILS (m^2)

Coverage (%)	Road Area (%)	Building Density[a] (%)	Wind Velocity (m/sec) 1.5	5.0	12.0	20.0
100%	10%	90.0%	7,900	18,000	68,000	248,000
	20	80.0	7,100	16,000	61,000	221,000
	30	70.0	6,200	14,000	54,000	197,000
70	10	63.0	5,500	12,000	48,000	174,000
	20	56.0	4,900	11,000	42,000	154,000
	30	45.0	4,300	10,000	37,000	137,000
45	10	40.5	3,600	8,000	31,000	113,000
	20	36.0	x	7,000	28,000	100,000
	30	31.5	x	6,000	24,000	88,000
25	10	22.5	x	x	17,000	64,000
	20	20.0	x	x	x	55,000
	30	17.5	x	x	x	x

Note: x denotes that the fire has extinguished itself.

a. Roof area to ground area.

Source: Hishida (1952).

In forest fires, weather plays an extremely important role. The intensity of a fire is sometimes analytically expressed by the following equation from Davis (1959).

$$I = Hwr,$$

where

I = fire intensity in Btu per second per foot of fire front

H = heat yield in Btu per pound of fuel

w = weight of available fuel in pounds per square foot

r = rate of spread in feet per second.

For a homogeneous idealized fuel which has a constant combustion rate, R, the fire intensity may also be written as

$$I = Rd,$$

where

d = width of burning strip of fuel.

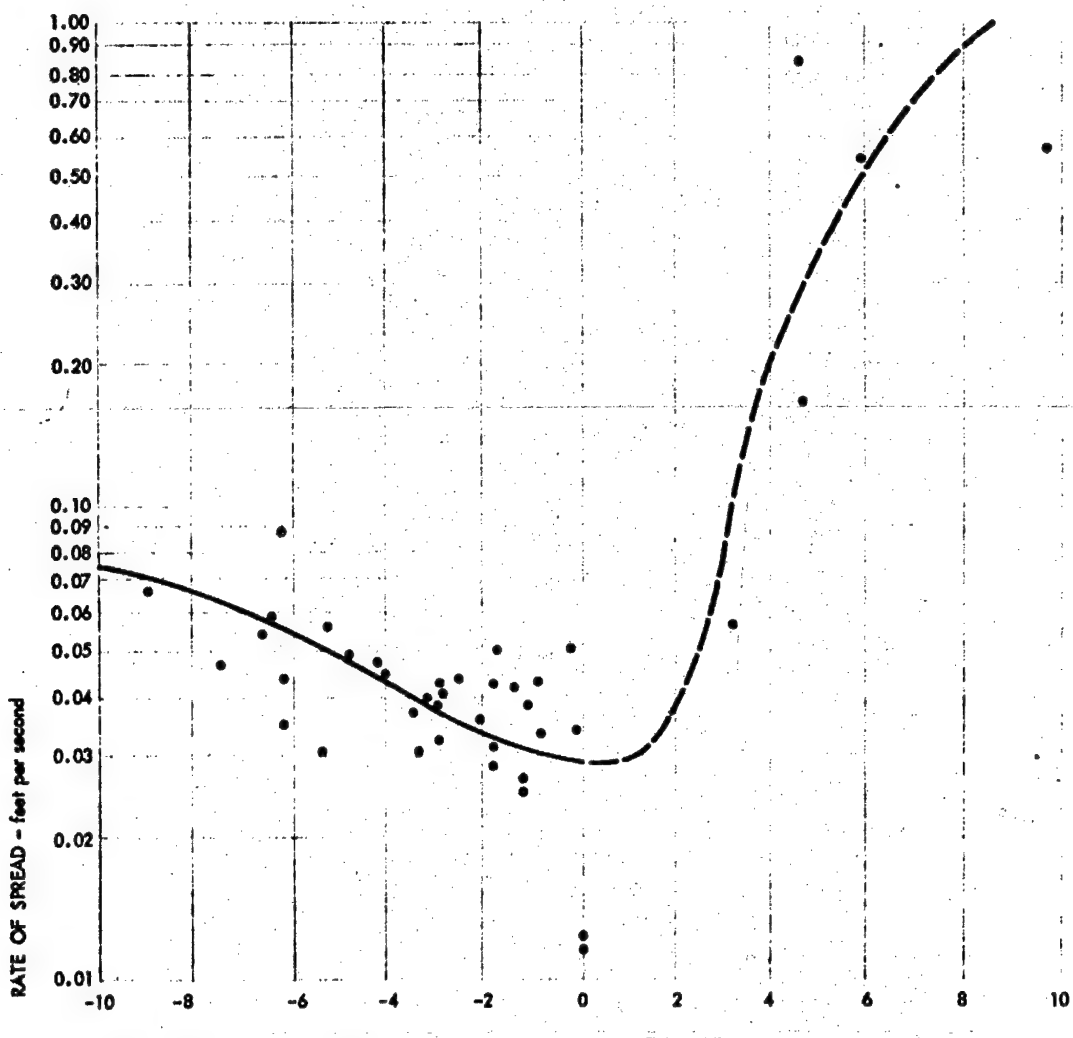
Figure C-18 is a scatter diagram of the rate of spread of a fire in light grass as a function of wind speed. It is interesting to note that the speed picks up as the wind blows more strongly into the fire--at least for low wind speeds. This is due, of course, to the increase in oxygen supplied to the flames. Using this figure, the intensity of a low intensity fire may be calculated. A typical example gives:

$$r = 0.04 \text{ ft/sec}, \; w = 0.1 \text{ lbs/ft}^2, \; H = 6{,}500 \text{ Btu/lb}, \; I = 26 \text{ Btu/sec/ft}$$

A majority of wildfires would have an intensity range from 100 to 1,000 Btu/sec/ft. Other approximations of rate of fire spread in forest fuels are given in Folweiler and Brown (1946), Fireline Notebook (1960) and various other Forest Service publications. These are useful in making quick estimates on the probable spread of fires on a short-term basis. (The Fireline Notebook, for example, requires as input data on the immediate past history of the fire.)

Figure C-18

RATE OF SPREAD OF FIRE IN LIGHT GRASS
(mostly for backing fires)



SOURCE: Davis (1959)

The rate of movement of low intensity fires in a homogeneous fuel bed has been experimentally and theoretically related to those variables directly associated with meteorological conditions; see Fons (1946). This work shows a close correlation between experimental and calculated fire spread rates. In Figure C-19 are shown some of the rate-of-spread results when all but one variable is kept fixed in each case. Here, λ is the "volume of voids per unit of fuel surface in inches" (a measure of compactness), t_o is the initial fuel temperature in degrees F, and σ is the surface/volume ratio of the fuel in inches^{-1} (a measure of the fineness). Although slope was not introduced directly as a factor in this model, Fons considers that for low-intensity fires, the effect of slope is to decrease the angle of the fuel and the hot gases and is, therefore, equivalent to adding a component of wind velocity.

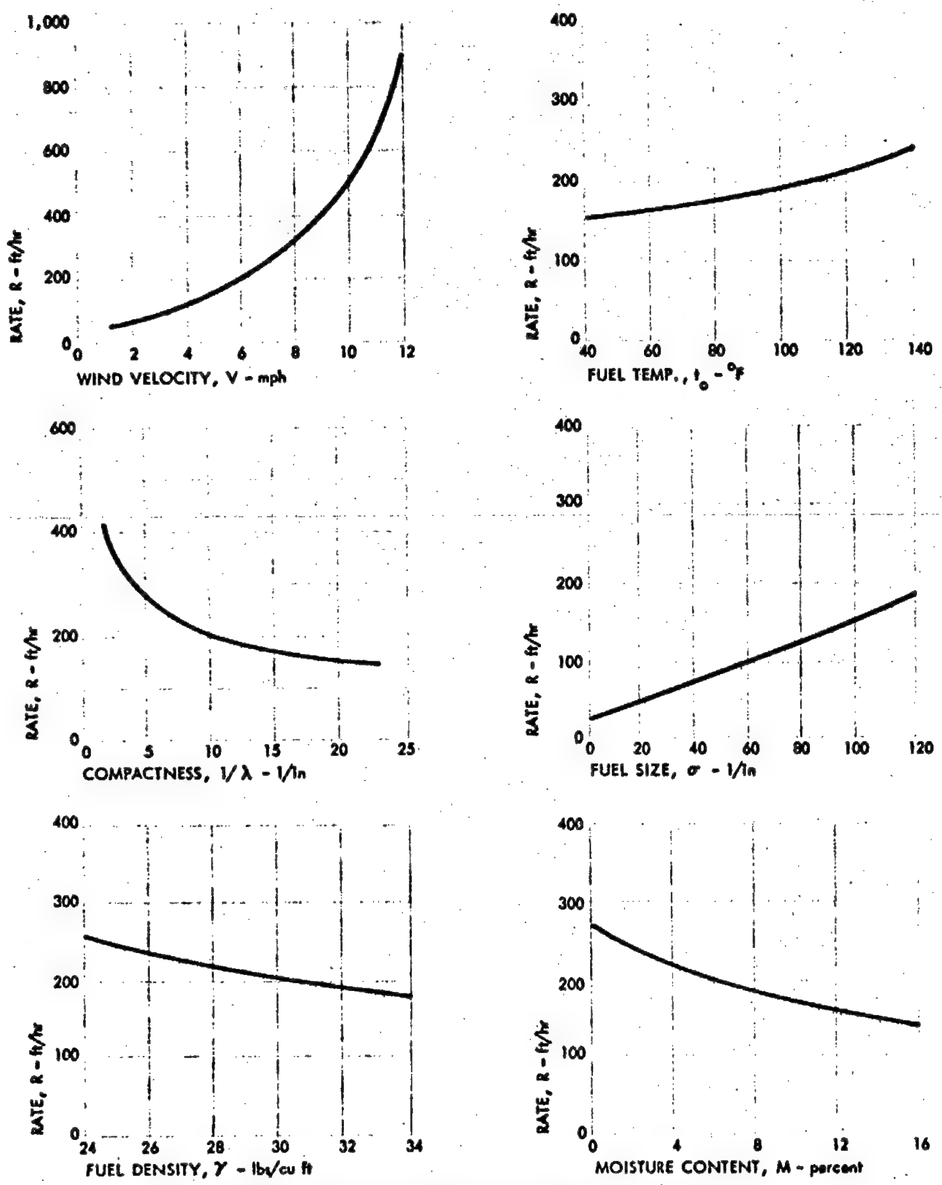
High intensity forest fires are considerably more complex. Their forward movement is governed by a transfer of ignition points ahead of the fire front from intense radiation of flashy fuels, from turbulent motion of hot gases ahead of the fire front, or from firebrands. A first attempt at modeling these mass fires is given in Davis (1959), on the basis of an energy criterion. Several other promising approaches have been suggested in the appendixes of A Study of Fire Problems (1961).

Other important projects currently under way should contribute significantly to the understanding of both urban and forest fire by attempting to identify important environmental parameters, to describe how they are related to the behavior of mass fires, and to present a model involving the parameters which may be used for predicting the behavior in terms of rates of spread, total burn-out area, and so on. For example, a project conducted by the U.S. Forest Service is attempting to relate weather parameters and derived fire indices (during critical fire periods) to actual fire records. This study will also include an investigation of the structure of turgid winds, with data taken from the Los Angeles basin area. As a third objective, research is under way to relate local and synoptic weather patterns.

The long range ecological effects of mass fires resulting from a nuclear attack have not been analyzed to any great extent. Dr. Mitchell and Dr. Hill of RAND Corporation (1961) have commented on the problem. Both feel that post-war recovery, though difficult, would be feasible. Preventative measures would help reduce the possibility of free-running fires. The long-range effects of fires on forests have been discussed in some detail by Davis (1959).

Figure C-19

EFFECT OF MEASURABLE VARIABLES ON RATE OF FORWARD SPREAD OF FIRES



NOTE: For each graph five variables are held constant while the sixth is varied over a practical range. When held constant, the variables have values as follows:

V - 6.0 mph; $1/\lambda$ = 10 inches^{-1}; γ = 31.6 lbs/cu ft; t_o = 100° F; σ = 128 inches^{-1}; M = 8 percent

SOURCE: Fons (1946)

Importance of Topography to Fire Vulnerability

The topography of a target area will significantly influence the development of both urban and forest fires. In the Bel Air fire--Wilson (1962)--for example, where many homes were built on hillsides, fires spread rapidly up the terrain. Houses with overhanging porches were especially vulnerable since they formed traps for heat which caused ignition underneath. The many case histories of forest fires give ample evidence that fires are greatly influenced by the terrain.

Davis (1959) points out that topography affects the fire danger in three ways:

"1. Slope. The effect of slope is much like that of wind, the steeper the slope the faster the rate of spread, other things remaining constant. Under strong solar radiation, wind is also generated on slopes.

"2. Altitude and aspect. The relative elevation of an area and its aspect, i.e., north, south, east, or west, has much effect on fire danger because of wide differences in climatic conditions affecting fuel moisture content and temperature.... Fuels on the south-facing slope may be dry enough to burn furiously, while similar fuels on an adjoining north slope will not carry fire at all.

"3. Accessibility. The ease or difficulty of getting to an area to control fire is a major factor in total fire danger."

For the nuclear fire potential, there are at least two other significant effects of topography. The first, which was pointed out earlier in this paper, is that topography may entirely shield certain areas from the blast, thermal, and possibly radioactive effects of the weapon.* The second is that firestorms are less likely to be created in broken terrain because of the unstable wind currents. This was clearly seen in the comparison of the Nagasaki (hilly area--no firestorm) and Hiroshima (flat area--firestorm developed) bombings.

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* In the Bel Air fire, for example, there were areas untouched by the fire over which firebrands flew at high altitude and created additional conflagrations.

Although fires will normally speed up a slope, it must be pointed out that if the slope is steep, embers or burning debris will often roll downhill, igniting new areas. Quantitatively, the effect of slope on fire spreadhas been considered in Civil Defense Urban Analysis (1953), Fireline Notebook (1960), and Fons (1946). The model for low-intensity fires given in Fons must be used with caution. Davis (1959) has this to say:

> "A fire spreading up a steep slope resembles a fire spreading before a strong wind. As a first approximation, the effects of slope and wind on small fires can be equated, but the analogy cannot be carried too far. If spotting and whirlwinds do not occur, the rate of buildup of firespread in heavy fuel in level country under the influence of a brisk wind is slowed down when the fire's intensity becomes high enough to produce a strong indraft opposite the direction of firespread. This self-regulating process does not occur when a fire builds up intensity in spreading upslope....Ordinarily a fire will spread upslope, but high-intensity erratic fires have not only spread upslope but downslope as well. Such fires have been known to travel across drainages (upslope and downslope) as though they did not exist."

Ridges may also create special effects, such as fire whirlwinds. A fire whirlwind is a tornado type wind activity which may be caused by strong convective currents over a large fire. The phenomenon is most likely to occur over fires in heavy fuel where updrafts are strong, or as would be the case in a nuclear attack, over areas where widespread fires are ignited simultaneously. The most troublesome characteristic of the fire whirlwind is that, unlike ordinary convection currents, it can break away from the main body of the fire and spread fire as it goes. The importance of whirlwinds in fire spreadcan probably be best illustrated from the following exerpt describing some documented observations; Davis (1959):

> "Some of the best examples of whirlwinds associated with a convection column are given in the description and excellent photographs by Hissong (1926) in the report of the large oil-tank-farm fire at San Luis Obispo, California, in 1925. These whirlwinds had true tornado characteristics. The photographs show long funnel-like structures suspended from far up in the convection column. Of those that reached the ground, some contacted the surface a considerable distance from the base of the fire and were observed from as much as three miles from the fire. Small buildings were destroyed by the whirlwinds. In his study of the Chicago fire on the night of October 8-9, 1871, Musham (1941) states that fire whirlwinds were probably

the major factor in the destruction of the city. These whirlwinds, too, must have reached near-tornado proportions because they lifted burning planks and dropped them on buildings far ahead of the main body of fire."

Not too many statistical data are available on fire whirlwinds. Graham (1955 and 1957) appears to be the only source of such information. He has found that topography evidently has an influence on their formation. In 20 out of 28 cases, the whirlwind occurred on a lee slope near the top of a ridge, the wind velocity above the ridge top being a determining factor. For a whirlwind formation, pressure reduction over a mountain ridge (equal to square of the wind speed) is a more important factor than steep lapse rates, which are always present wherever there are large convection currents.

Appendix D

RELATIONSHIPS BETWEEN TARGETS AND FIRE DEVELOPMENT AND SPREAD

Much has already been said in this report about targets, their interactions with the direct thermal radiation from nuclear weapons, and the effect of weather on their vulnerability. Some additional data concerning target elements, fire development, and fire spread will now be presented.

Materials and Fire Processes

Thermal Properties of Materials

Many handbooks describe the physical, chemical, and thermal properties of materials. For forest fuels, Byram, et al. (1952) is a concise reference for a description and listing of the following properties: fuel moisture, specific heat capacity, net heat required to ignite wood, heat of decomposition, thermal conductivity, dimensions and structure of combustible material, and thermal absorptivity. The optical characteristics of various materials (transmittance, reflectance, absorptance) have been studied by the Naval Material Laboratory in connection with its research on the effects of high intensity thermal radiation; see Byrne and Mancinelli (1954).

For additional general information, Salzberg, et al. (Phase I, 1960) and Publications on Fire Research (1962) present good abstracts concerning the properties of fuels as related to ignition and combustion.

Ignition of Materials

The ignition of materials by the direct thermal radiation from a nuclear weapon has been covered in Appendix B. Ignition by less intense, but more prolonged heat sources and the general processes involved in burning are extremely complex and have never been thoroughly understood or described.

In Squire (1961), Weatherford (1962), and Squire and Foster (1961), theoretical models have been developed which describe the general theory

of the ignition and burning of wood. Good references to research on the mechanism of burning are given in these reports.

Classified paragraph on ignition of materials has been deleted.

Lawson and Simms (1952) have experimentally determined the intensity of radiation required to ignite wood spontaneously both with and without a pilot flame one-half inch from the surface of the material. This radiation, which is of the order of magnitude of that which might be received from a burning building, is of much lower intensity and of longer duration than that produced by atomic weapons. The expression relating time for ignition, t, to the critical ignition intensity, I, is the following:

$$(I - I_p)t^{2/3} = 0.025 \times 10^6 (K\rho s + 68 \times 10^{-6})$$

where

I_p = critical intensity for pilot ignition (cal/cm^2/sec)

K = thermal conductivity

ρ = density

s = specific heat of the material.

The corresponding expression for spontaneous ignition was found to be

$$(I - I_s)t^{4/5} = 0.05 \times 10^6 (Ks\rho + 35 \times 10^{-6}),$$

where

I_s = critical intensity for spontaneous ignition.

The requirements for the spontaneous ignition of other materials are shown in Table D-I; Table D-II gives ignition requirements for materials when a pilot flame is present. Included in these tables are estimates for the time required to ignite the materials. Additional data for the ignition times of wood are given in Bomb Damage Analysis (1949). The self-ignition of liquids and of plastics is considered in Setchkin (1949 and 1954), respectively. The National Bureau of Standards has an active program concerned with (1) the measurement of flammability of materials, (2) the thermal behavior of backing of laminated materials, (3) the influence of moisture, and (4) methods for measuring heat release of materials.

Flamespread and Potential Heat in Building Materials

For materials used in building construction, the National Bureau of Standards has defined a "flamespread index" which is particularly useful in evaluating the effect of fire-retardant coatings on wood-base materials; see Gross and Loftus (1958) and Gross (1960). This surface flammability index is concerned with the rate at which flames travel along the surfaces of materials. The degree of combustibility of a building material, however, is more closely related to the extent to which the bulk of a representative wall, ceiling, or floor element may contribute to heat to support active combustion. The degree of combustibility is perhaps more appropriately called the "potential heat." The Bureau of Standards has a program which is attempting to standardize the definition of potential heat and to develop a method for its determination. In this program, many building materials have been studied; see Loftus, et al. (1961).

Heat Transfer through the Ground and through Underground Shelter Materials

The temperature within underground shelters during a mass fire is critically dependent on the conduction of heat from the rubble above through the soil, concrete, steel, wood, or other intervening materials. For various thicknesses of the four mentioned materials, Broido and McMasters (1960) have computed the time necessary for the temperature of the inside surface to increase from 60°F to 90°F when the outside of the solid, originally at 60°F, was assumed to rapidly reach and be maintained at 2000°F.

Davis (1959) states that in forest fires, above-surface temperatures may exceed 1500°F in hot fires; temperatures at the surface of 400°F and higher are common. In this presentation, he was mainly concerned with the depth of heat penetration into the mineral soil and the problems of

Table D-I

SPONTANEOUS IGNITION OF MATERIALS EXPOSED TO RADIATION

Material	Intensity Btu ft^{-2} sec^{-1}	Time to Ignite, sec.
Cotton print	2.54	8.7
Cotton print, washed	2.54	10.4
Gabardine, white	5.16	5.4
Gabardine, olive	4.06	6.8
Linen	3.50	9.1
Linen, washed	3.17	11.2
Rayon	5.16	3.9
Sateen, washed	3.76	7.3
Whitewood	2.95	60.0
Winceyette	4.02	4.3
Wool, blue	6.19	18.0

Source: Simms and Walters (1951).

Table D-II

PILOT IGNITION OF MATERIALS EXPOSED TO RADIATION

Materials	Intensity Btu ft^{-2} sec^{-1}	Time to Ignite, sec.
Cotton print	1.95	11.8
Cotton print, washed	2.14	17.5
Painted wood ignited by flying brands	1.47	--
Wood ignited by flying brands	0.37	--

Source: Lawson and Hird (1953).

reforestration. Tables D-III and D-IV show some of the results of temperature readings at various depths of the soil during forest and brush fires.

Table D-III

MAXIMUM SOIL TEMPERATURES DURING FOREST FIRES[a,b]
(In Degrees Fahrenheit)

Depth (inches)	"Natural" Fires in Light Fuels Burning 3/4 hr	Maximum-intensity "Natural" Fires in Light Fuels Burning 2 hr	Maximum-intensity Fires Burning in Heavy Fuels: Burning 2 hr	Maximum-intensity Fires Burning in Heavy Fuels: Burning 8 hr (stoked)
Surface	290	480	c	c
1	130	235	350	480
3	--	145	210	430
6	--	95	147	185
9	--	59	104	136
12	--	54	70	116

a. After Beadle (1940).
b. Temperatures from a number of tests averaged. Those obtained at 1- and 3-inch depths from chemical-compound melting points averaged to nearest 5°.
c. Not determined.

Source: Davis (1959).

Structures and Fire Processes

Combustibility of Buildings

Section 8, Chapter IX of the Fire Protection Handbook (1962) defines in detail five types of construction. The five classifications are (1) fire-resistive, (2) heavy timber, (3) noncombustible, (4) ordinary, and (5) wood frame.

In addition to being categorized by the materials used in their construction, structures may also be categorized according to the percentage

Table D-IV

LITTER AND SOIL TEMPERATURE IN CALIFORNIA CHAPARRAL TYPES DURING BURNING[a]

Vegetation	Depth of Thermocouples (inches)	Maximum Temperatures, (°F)	Minutes To Reach Maximum Temperature	Minutes Temperature Remained over 150°F
Chamise, fairly dense grasses and weeds	On soil surface	635	9	3
	3/4 in. in soil	320	9	12
	1 1/2 in. in soil	230	16	17
Mixed chaparral of blue oak, dwarf interior live oak, wedgeleaf ceanothus, with scattered herbs	1/2 in. in duff	840	4	40
	1/2 in. in soil	410	7	61
	1 1/2 in. in soil	235	14	74
Wedgeleaf ceanothus with scattered grasses	1/2 in. in litter	300	5	11
	1/2 in. in soil	200	1	5
	1 1/2 in. in soil	b		
Common manzanita, scattered grasses and weeds	1/2 in. in litter	960	8	34
	1 1/2 in. in soil	215	16	17

a. After Sampson (1944).
b. Below 150°F. Instrument does not record below this temperature, and hence no reading.

Source: Davis (1959).

of their floor areas covered by combustible materials. Table D-V, which relates this variable to utilization of structures, was used during World War II to compute a mean area of effectiveness of incendiary bombs.

Table D-VI gives the results of a survey of structures by exterior material in some cities of the United States. Table D-VII shows the percentages of fire-resistive and combustible structures in five U.S. cities in 1940. Wilson (1962) presents a very strong argument against the use of shingles on homes. Table D-VIII shows the distance of flamespread and penetration time for various roofing materials, as given by Lawson and Thomas (1956). Salzberg, et al. (Phase I, 1960) lists additional studies on types of construction and their importance to fire spread. Other data are available through insurance companies, Sanborn maps, the National Fire Protection Association, and other agencies.

Development of Fires within and between Buildings

The literature on fire development within structures and fire spread between structures is extensive and cannot be reviewed here in detail. The reader is referred to reports issued by the National Fire Protection Association, the National Board of Fire Underwriters, and the Directory of Fire Research in the United States (1961). Salzberg, et al. (Phase I, 1960) gives an extensive bibliography on the burning of structures and the spreading of fire between structures. Several papers have been presented in Berl (1961) for the theory of burning within rooms, the convection currents above a burning house, and the general problem involved in using laboratory or theoretical models to describe fire processes.

Within a single room or compartment of a building, fire develops in stages; see Lawson and Thomas (1956). First, the most combustible substances are ignited. Then the heavier materials will begin to burn. When the heat is great enough, flammable gases will be generated from other materials. Within five to twenty minutes, an instantaneous spread of surface flaming of combustibles will occur due to heating and ignition of gaseous decomposition products. This explosive phenomenon is called flashover.

As a fire develops within a building, the temperature increases according to the approximating curve, Figure D-1, developed by the American Society for Testing Materials, the National Fire Protection Association, the National Bureau of Standards, the National Board of Fire Underwriters, and the Factory Mutual Laboratories. The fire resistance of a wall is defined as the length of time before its collapse when subjected to the heating curve given in the figure. Roughly speaking, this time can be considered as the time from flashover.

Table D-V

PERCENTAGE OF FLOOR AREA COVERED BY COMBUSTIBLE MATERIAL

5 Percent (noncombustible)	10 Percent (noncombustible)	20 Percent (slightly combustible)	30 Percent (moderately combustible)	40 Percent (highly combustible)	50 Percent (extremely combustible)
----------	----------	---------- Stores	----------	----------	----------
----------	----------	---------- Chemical	Plant ----------	----------	----------
		---------- Packing	----------	----------	
		----- Aircraft Assembly	-------		
	------ Heat Treatment	--------			
Boiler Houses Casting Halls Compressors Engine Test Cells Generators Power House Pumps	Forge Foundry Heavy Machine Shops MG Firing Range Metal Press Shop Milling except Gear Cutting Storage Hangars Tool Shop	Aircraft Engine Assembly Flight Hangars Gear Cutting Light and Medium Machine Shops Storage Garages Sub Assembly of Components Test Laboratories	Air Frame Assembly Repair Hangars Special Machine Shops (High Speed Automatics)	Canteens Drafting Rooms Offices Paint Shops Repair Garage Spray Painting	Special Hazards Weaving Mills Workers Huts

Source: The Selection of Weapons . . . (1947).

Table D-VI

TYPES OF STRUCTURES IN U.S. CITIES, BY EXTERIOR MATERIAL

City	Total Structures Reported	Wood	Brick	Stucco	Other Materials[a]
Chicago	382,628	131,148	238,959	5,797	6,724
Detroit	267,677	165,488	94,533	1,923	5,933
New York	591,319	236,879	299,482	41,661	13,297
San Francisco	105,180	61,172	2,334	40,902	722
Washington	156,359	48,971	95,939	5,764	5,685

a. Includes blast-resistant and fire-resistive buildings.

Source: Civil Defense Urban Analysis (1953).

Table D-VII

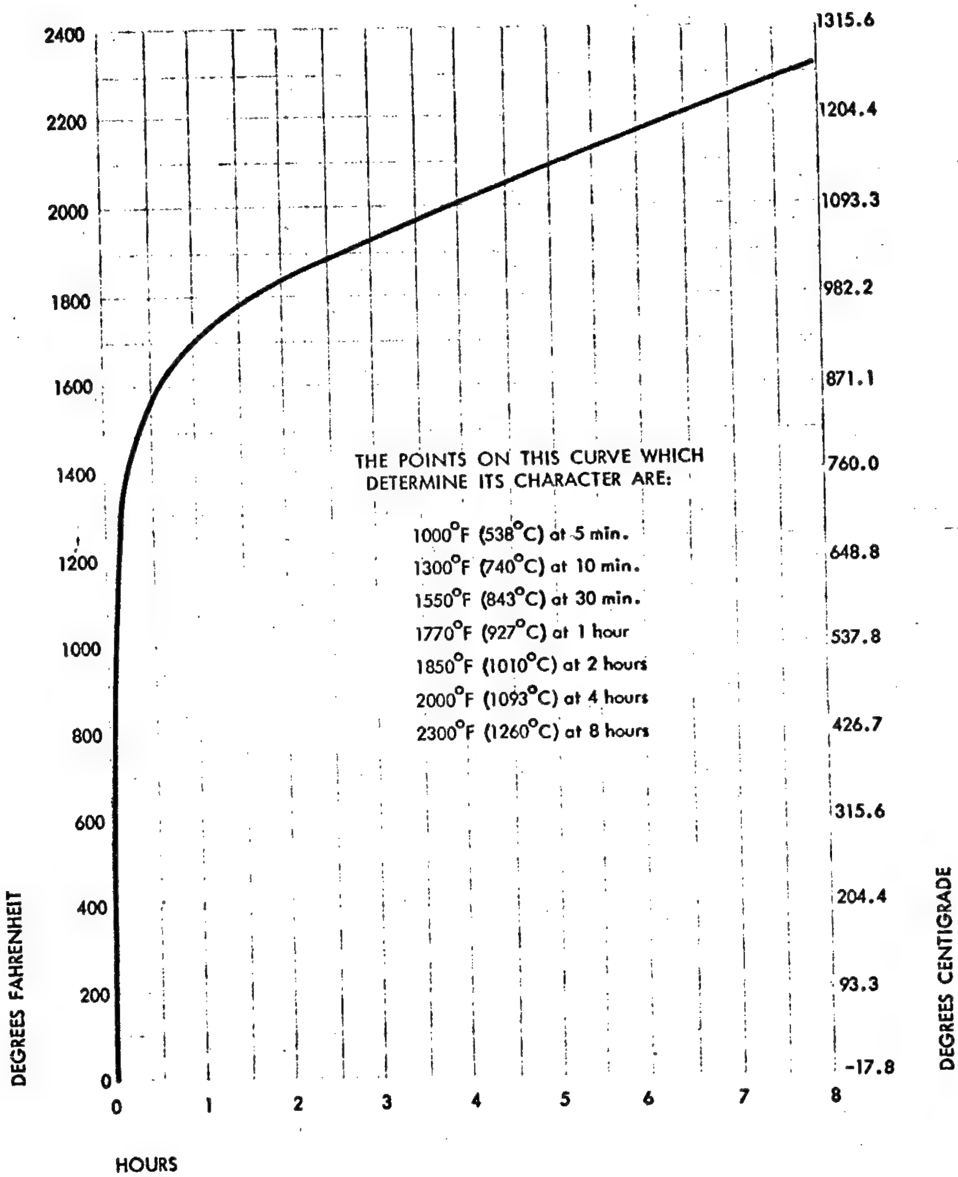
PERCENTAGES OF FIRE-RESISTIVE AND COMBUSTIBLE STRUCTURES IN FIVE U.S. CITIES (1940 Census)

City	Percentage of Structures by Construction (U.S. cities)	
	Fire-Resistive Construction	Combustible Construction
Chicago	1.7	98.3
Detroit	2.2	97.8
New York	2.3	97.7
San Francisco	Less than 1	99.+
Washington	3.6	96.4

Source: Civil Defense Urban Analysis (1953).

Figure D-1

STANDARD TIME-TEMPERATURE CURVE



SOURCE: Bomb Damage Analysis (1949)

Table D-VIII

FLAMESPREAD AND PENETRATION FOR VARIOUS TYPES OF ROOFS

Roof	Penetration Time	Distance of Flame-spread
Felt on 7/8 in. wood 1 layer 40-lb, self-finished organic-based felt on one layer 25-lb saturated felt	11 min	33 in.
As above, but felt asbestos-based	1 hour, 20 min	20 in.
Wood shingles	6 min	Not measured
Polyester roof light	6 min	Not measured

Source: Lawson and Thomas (1956).

The fire severity of various types of burning structures has been ranked according to the fire resistance of their walls. Table D-IX and D-X show this general guide to the severity of fires to be expected in various classes of occupancy.

Classified paragraph concerning spread of fire between buildings has been deleted.

Table D-IX

ESTIMATED FIRE SEVERITY BY OCCUPANCY

Occupancy	Combustibles in Occupancy (lb per sq ft of floor area)	Equivalent Fire Severity (approximately equivalent to that test under standard curve for the following periods)
Residential	5 to 10	1/2 to 1 hr
School	5 to 10	Less than 1 hr
Institutional	5 to 10	1/2 to 1 hr
Assembly	Under 10	Less than 1 hr
Business (including mercantile)	10 to 15	1 to 1-1/2 hrs
Industrial	Varies, ±30	Varies to 3 hrs or more
Storage	Varies, ±40	Varies to 4 hrs or more
Hazardous	Over 40	Over 4 hrs

Source: Bomb Damage Analysis (1949).

Table D-X

ESTIMATED FIRE SEVERITY FOR OFFICES AND LIGHT COMMERCIAL OCCUPANCIES

Combustible Content, Including Finish Floor and Trim (lb/ft^2)	Heat Potential Assumed[a] (Btu per ft^2)	Equivalent Fire Severity (approximately equivalent to that test under standard curve for the following periods)
5	40,000	30 mins
10	80,000	1 hr
15	120,000	1-1/2 hrs
20	160,000	2 hrs
30	240,000	3 hrs
40	320,000	4-1/2 hrs
50	380,000	7 hrs
60	432,000	8 hrs
70	500,000	9 hrs

a. Heat of combustion of contents taken at 8,000 Btu per lb up to 40 lb per sq ft., 7,600 Btu per lb for 50 lb, and 7,200 Btu for 60 lb and more to allow for relatively greater proportion of paper.

Source: Bomb Damage Analysis (1949).

Structural Density and Its Importance to Fire Spread

A parameter which is often considered important to fire spread between buildings is the density of the buildings within a city (ratio of roof area to total area). This is discussed in Fire Spread in Urban Areas (1955), in Civil Defense Urban Analysis (1953), and by Bond (1946).

A method for estimating the building density from Sanborn maps is described in Civil Defense Urban Analysis. Appendix A of this reference lists five types of maps (together with sources) and some supplementary materials which are useful for target analysis; Appendix B suggests uses to which these maps and other data can be applied. Included are many items concerning fire damage estimates, such as fuel value of buildings for detailed studies of fire susceptibility, depth and spread of rubble which may affect the passability of streets after a bombing, industrial plants with highly flammable or explosive materials which may contribute to mass fires, and so on. Methods for making evaluations concerning these are not given.

As typical building densities within cities, the firestorm area of Hamburg, Germany, had a building density of about 30 percent; central portions of German cities often had building densities of about 40 percent; and Hiroshima had a density of 27 to 42 percent in the 4-square-mile city center. In Japan during World War II it was reported that Tokyo had 22.5 square miles of residential area 46 percent built up (Fire Effects of Bombing Attacks, 1959). In ten other Japanese cities, the building densities for various districts were 11 to 49 percent in residential areas, 33.6 to 49 percent in manufacturing areas, and 28 to 50 percent in mixed manufacturing and residential areas.

Based on the data from World War II, Civil Defense Urban Analysis (1953) estimates that isolated fires with no significant risk of fire spread correspond to a building density of 0 to 5 percent, local spreading fires with no firestorms or conflagrations correspond to a building density of 6 to 20 percent, and firestorms or conflagrations are possible if the building density is more than 20 percent.

Table D-XI presents a correspondence between the average built-upness (building density) and the exposed areas burned, based on Japanese experience. Miller (1962) has derived the following analytic expression from these data:

$$b_e = 1.88\, B^{1.2} ,$$

Table D-XI

PERCENTAGE OF DAMAGE BY OCCUPANCY ZONES

Zone	Average Built-upness (%)	Exposed Areas Burned (%)
Dense residential	45 %	72%
Medium residential	30.6	46
Sparse residential	15.5	20
Mixed residential and manufacturing	35	44
Manufacturing	41	22
Transportation	14	15
Storage	37.6	22

Source: Bomb Damage Analysis (1949).

where b_e is the fraction of exposed areas burned and B is the fractional building density. He has also found approximate analytic expressions for spread probability as a function of firebreak distance, as shown in Figures E-5 through E-7.

Vulnerability of Humans in Mass Fires

Mass fires create many hazards to human life. Within shelters which are not specially prepared for the threat of mass fires, the principal hazards possibly include (1) oxygen depletion, (2) carbon dioxide, (3) carbon monoxide, and (4) heat. Other toxic gases may also be a threat, but they are only found in special cases. Broido and McMasters (1960) have collected data on the tolerance levels of humans to the four items above. The results are shown in Tables D-XII through D-XIV and Figure D-2.

The data describing casualties in the incendiary raids on Germany have been analyzed in considerable detail by Earp (1953) and Bond (1946). In spite of the great devastation created by the firestorm in Hamburg, of the 280,000 people in the firestorm area, only about 40,000 were killed. Earp accounts for the remaining 240,000 as shown in the tabulation on page D-20.

Table D-XII

EFFECTS OF OXYGEN DEFICIENCY

Oxygen Content of Inhaled Air (percent)	Effects
20.9%	No effects; normal air.
15	No immediate effect.
10	Dizziness; shortness of breath; deeper and more rapid respiration; quickened pulse, especially on exertion.
7	Stupor sets in.
5	Minimal concentration compatible with life.
2 -3	Death within one minute.

Source: Broido and McMasters (1960).

Table D-XIII

EFFECTS OF CARBON DIOXIDE[a]

Carbon Dioxide Content of Inhaled Air (percent)	Effects
0.04%	No effects; normal air.
2.0	Breathing deeper; tidal volume increased 30%.
4.0	Breathing much deeper; rate slightly quickened; considerable discomfort.
4.5- 5	Breathing extremely labored, almost unbearable for many individuals. Nausea may occur.
7 - 9	Limit of tolerance.
10 -11	Inability to coordinate; unconsciousness in about 10 minutes.
15 -20	Symptoms increase, but probably not fatal in 1 hour.
25 -30	Diminished respiration; fall of blood pressure; coma; loss of reflexes; anesthesia; Gradual death after some hours.

a. Oxygen content normal.

Source: Broido and McMasters (1960).

Table D-XIV

EFFECTS OF CARBON MONOXIDE[a]

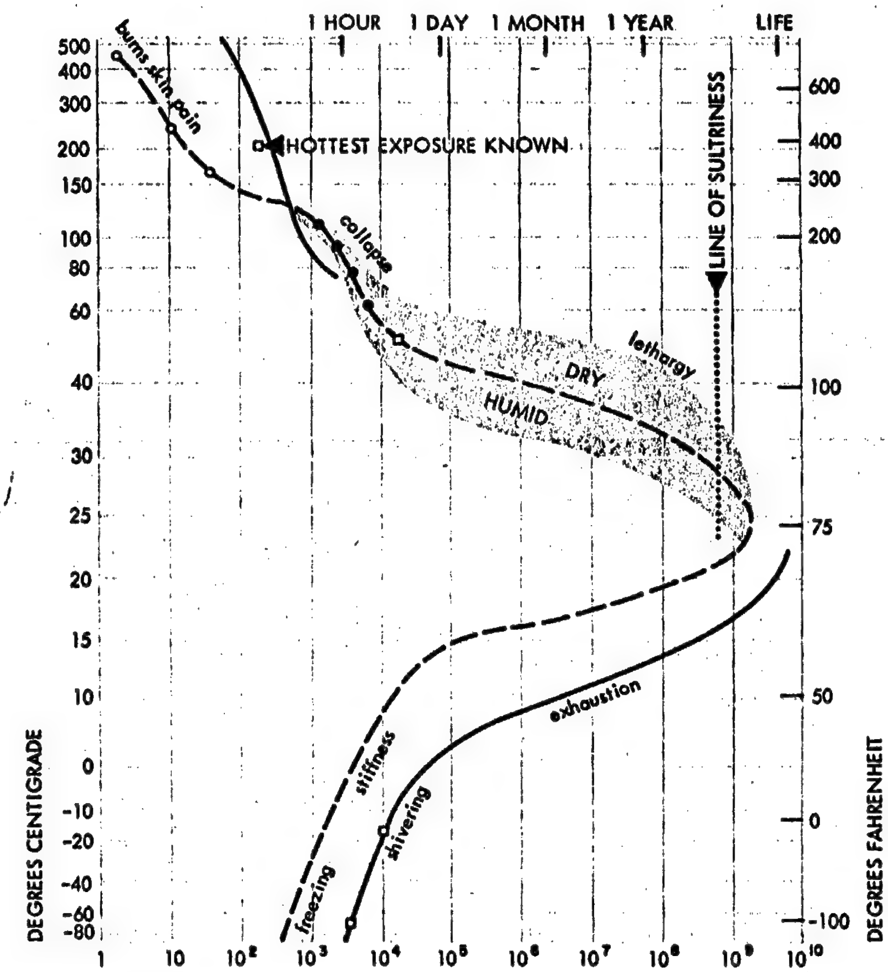
Carbon Monoxide Content of Inhaled Air (percent)	Effects
0.02%	Possible mild frontal headache after 2 to 3 hours.
0.04	Frontal headache and nausea after 1 to 2 hours. Occipital (rear of head) headache after 2-1/2 to 3-1/2 hours.
0.08	Headache, dizziness, and nausea in 3/4 hour. Collapse and possible unconsciousness in 2 hours.
0.16	Headache, dizziness and nausea in 20 minutes. Collapse, unconsciousness, and possible death in 2 hours.
0.32	Headache and dizziness in 5 to 10 minutes, unconsciousness and danger of death in 30 minutes.
0.64	Headache and dizziness in 1 to 2 minutes, unconsciousness and danger of death in 10 to 15 minutes.
1.28	Immediate effect. Unconsciousness and danger of death in 1 to 3 minutes.

a. Oxygen content normal.

Source: Broido and McMasters (1960).

Figure D-2

SAFE EXPOSURE TIME FOR MAN IN EXTREME THERMAL ENVIRONMENT



— — — BODY NUDE OR PARTS EXPOSED
——— CLOTHED, 1 cm THICK
o BODY OR PARTS EXPOSED
• LIGHTLY CLOTHED
□ CLOTHED, FACE BARE

SOURCE: Broido and McMasters (1960)

Rescued by police, medical, rescue, and armed forces	30,000
Rescued by fire and decontamination services	15,000
Survived in nonbasement shelters (100 percent of occupants)	53,000
Survived in basement shelters or escaped by their own initiative	142,000
	240,000

By carefully studying the autopsy reports of many of the victims found both in the shelters and on the streets of Hamburg, Earp (1953) has concluded that (1) heat and carbon monoxide were the two most frequent causes of death in large scale H.E./I.B. raids, and (2) in the streets, deaths from heat effects predominate, whereas in the shelters, deaths were mainly due to carbon monoxide. The number of autopsies performed was too small to provide a reliable estimate on the proportion of the total deaths due to carbon monoxide.

The casualty figures for the Hiroshima, Nagasaki, Tokyo, and other Japanese cities are shown in Table D-XV. Most of the casualties in the incendiary bombings--all except the Hiroshima and Nagasaki cases--were caused by the effects of conflagrations or firestorms.

Vegetation and Fire Processes

Wildland fuels must be classified both by rate of spread and resistance to control; see Davis (1959). For example, a grassland fire may have a very high rate of spread but is easily brought under control. A fire in a fresh slash of conifers, on the other hand, has a low rate of spread but is extremely difficult to master. (Such a classification may be useful in urban conflagrations.) Table D-XVI shows the variation in the rate of fire spread and the resistance to control for certain fuel types.

Relationship of Vegetation to the Vulnerability of Structures

Practically no information exists concerning the importance and statistical distribution of vegetation near structures. In some cases, vegetation near structures is a hazard as, for example, in the Bel Air conflagration; see Figure D-3. In other cases, green trees or shrubs will be important in preventing the spread of fires by radiation, firebrands, and convection currents from hot gases. Nakamura (1951 and 1952)

Table D-XV

EFFECTS OF WORLD WAR II BOMBINGS ON JAPAN

	Hiroshima	Nagasaki	Tokyo	Average of 93 Urban Attacks
Planes	1	1	279	173
Bomb load	1 atomic	1 atomic	1,667 tons	1,129 tons
Population density per square mile	35,000	65,000	130,000	unknown
Square miles destroyed	4.7	1.8	15.8	1.8
Killed and missing	70/80,000	35/40,000	83,600	1,850
Injured	70,000	40,000	102,000	1,830
Mortality rate per square mile destroyed	15,000	20,000	5,300	1,000
Casualty rate per square mile	32,000	43,000	11,800	2,000

Source: Bond (1949).

Table D-XVI

RATE OF SPREAD AND RESISTANCE TO CONTROL OF SELECTED EASTERN FUEL TYPES

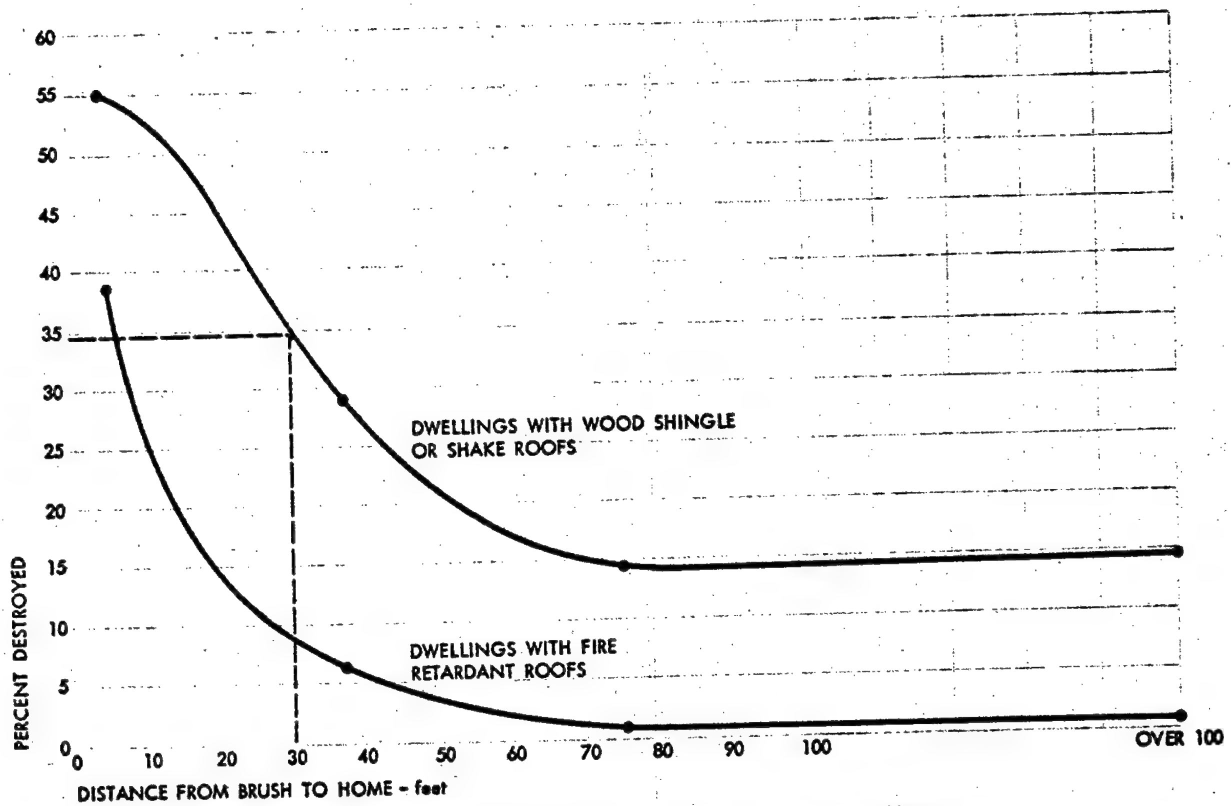
	Rate of Spread			Resistance to Control	
		Chains Perimeter Increase per Hour*			Rate of Held-Line-Construction,
Fuel Type	Classification	Average	Fastest 25%	Classification	Chains per Man-Hour[a]
Northern conifers, 4 in. +	L	12.1	21.7	M	1.8
Northern conifers, cutover, duff, no slash	H	30.2	86.7	H	1.3
Northern and Appalachian hardwoods, 3 in. +	M	20.7	47.4	M	2.1
Southern pine, 6 in. +	M	22.7	53.0	L	2.8
Conifer slash, fresh	L	15.8	35.8	E	0.4
Hardwood and southern pine slash	M	25.4	60.9	M	1.8
Grass, ferns, and weeds	H	26.8	58.8	L	3.2
Scrub oak	E	35.6	85.2	M	1.9

a. Rate of spread and resistance to control classified as L = low, M = medium, H = high, E = extreme.

Source: Davis (1959).

Figure D-3

EFFECT ON CONFLAGRATION OF VEGETATION NEAR STRUCTURES



NOTE: This graph of data from the conflagration shows the importance of brush clearance around homes. Note that with brush spacing 30 feet from the home, 8 percent of the fire-retardant-roofed homes were destroyed while 34 percent of the wood-shingle or shake-roofed homes were destroyed. Thus, a fire-retardant-roofed home was 4 times safer at 30 feet than the wood-shingled home. At 75 feet the fire-retardant-roofed home was 8 times safer than the wood-shingled home.

SOURCE: Wilson (1962)

has conducted experiments to determine the shielding protection afforded by trees to a structure exposed to radiation from burning wooden buildings. The results have been used in a theoretical development of a model based on a solid angle projection scheme.

Classified paragraph on fire spread has been deleted.

Conversely, a case where vegetation played an important role in aiding the spread of fire is cited by Broido and Trilling (1955). In this example, on January 17, 1950, a brush fire spread to Camp Carson, Colorado; completely destroyed 92 buildings; and claimed 8 lives. Report on the Berkeley. . .Conflagration. . .(1923) gives an example of the spread of a rural grass fire into a city (Berkeley, California) which resulted in extensive urban damage.

Vegetation in, or adjacent to, cities has never been studied in detail for its relation to fire spread. For information on vegetation in cities, Sanborn maps may be of some help since they depict open spaces and parks. For the interface of cities and rural areas, maps of timber stands and vegetation have been drawn for many areas of the state of California; see Legends and Supplemental Information. . .(1955). These maps divide the land into small parts on the basis of age and density of timber or density of shrubs. From them, the interrelation of forests and some exemplary California cities may be ascertained. Similar maps may be available for other states and might be useful in making damage estimates of mass fires. Of course, these maps change rapidly with the increased development of suburbs.

Fuel Densities in Mass Fires

Table D-XVII gives examples of the reported fuel density in some mass fires.

Table D-XVII

FUEL DENSITIES IN MASS FIRES

Fuel Density (tons/acre)	Name or Location of Fire	Reference
80.	Donner[a]	Forest Service
7.5	France[a]	Berl (1961)
50.	Bel Air	A Report on Physical Damage in Japan (1947)
15.-20.	Topanga Canyon	Brown (1962)
100.	Briones[a]	Broido and McMasters (1960)
125.	Camp Parks[a]	Broido and McMasters (1960)

a. Experimental.

Source: Stanford Research Institute.

As a comparison of fuel densities, Brown (1962) states that in some California cities the fuel densities are as much as 75 to 100 tons/acre, which does not seem unreasonable when considering the brush fires of Bel Air.

Appendix E

COUNTERMEASURES

Countermeasures to the Thermal Pulse

Although the subject of countermeasures to the intense thermal radiation from a nuclear detonation is being treated more comprehensively in other studies (see Attenuation and Absorption . . . 1953-62), it is included here to complete the general survey information of this report. At the time of this writing, a project sponsored by the Office of Civil Defense is under way at United Research Services (URS). In the URS study, special attention is being directed to countermeasures based on the absorption rather than the scattering of thermal energy. (The latter has received primary emphasis in the literature.)

Artificial Fog and Smoke Generation

Classified paragraph on artificial fog and smoke generation has been deleted.

The costs for cloud protection are nominal. Capital costs are estimated at $8,000 per square mile--more for small cities less for large ones. Operating costs would be about $400 per square mile per

alert. For Los Angeles with an area of about 400 square miles, this amounts to a capital investment of about $3,000,000 and a cost of $25,000 per alert. Maintenance costs are unknown. It is estimated that the cloud could be effective with a minimum of 15 minutes' warning; however, one to two hours are considered optimum.

Two classified paragraphs on smoke generation have been deleted.

The military services have also been interested in the use of smoke to reduce thermal radiation hazards; however, many of their reports are concerned more with the use of smoke generators in tactical warfare than in mass, strategic protection; see Mahoney, et al. (1960), Ford (1953), and <u>Potential of Industrial Smoke</u> . . . (1955). In Mahoney, it was found that absorbing smoke is much more effective than scattering smoke in reducing thermal radiation from a 6000°K source (e.g., a nuclear fireball) and for smoke concentrations of 0.5 gm/sq meter. The values of the transmissivity of the tested smoke were too small to be measured by the apparatus used in the experiments.

Classified Table E-I pertaining
to smoke generation has been
deleted.

Some weapons tests have incorporated smoke into the test plan to investigate the absorption of thermal radiation. In UPSHOT-KNOTHOLE--see Morris, et al. (1955), Shelberg and Martin (1958), and Enguist and Forsthoff (1954)--for example, a black layer of smoke having an average height of 80 to 90 feet above the ground surrounded ground zero of Shot 10 (15 kt) as shown in Figure E-1. The concentration was estimated to be 125 to 425 gal/sq mi. For this test a nuclear device of less than 10 kt was detonated on a 300-foot tower. The resulting absorption and the increase in air temperature due to absorption are shown in Table E-II. The increase in air temperature is negligible compared to the heating produced by the interaction of the transmitted thermal radiation with the ground.

The radiant exposure in the air-zero direction measured below the screen ranged from 17 to 1.5 cal/cm^2 at 1,000 to 2,400-foot ground range, respectively, and the attenuation was 78 to 90 percent throughout this range and resulted in a radiant exposure of only 3 cal/cm^2 at approximately the 9-psi ground range and beyond.

In the URS project, methods of generating smoke screens and cost-effectiveness analyses are being considered. Possible disadvantages, such as loss of visibility to automobile drivers, are being considered.

Table E-II

SHOT 10, ABSORPTION OF THERMAL RADIATION AND HEATING OF AIR IN THE SMOKE LAYER

Classified Table E-II concerning smoke generation has been deleted.

Classified Figure E-1 pertaining to smoke generation has been deleted.

Warning

Warning can be considered as an operational countermeasure to the radiant energy from a nuclear detonation. As was pointed out earlier, even the slightest warning may be sufficient to protect individuals from retinal and flashburn. The effectiveness of other countermeasures is also more assured with warning since time would be required to activate them. Smoke generators would require time to create a protective covering of an area. Other operations, such as closing the windows in a residence or shutting the venetian blinds, would markedly reduce the danger from the thermal flash within buildings.

Elimination of Kindling Fuels

Since the initial fires would be started in kindling fuels, a general clean-up campaign would reduce the ignition points and hence the probability of the development of mass fires. In actual weapons tests, Glasstone (1962), three small houses were constructed to illustrate the importance of such a clean-up campaign. The houses were exposed to 12 calories per square centimeter. Those houses which were badly weathered or had trash in the yards were destroyed while the well-maintained house was only scorched. As a rough indication of the improvements that could be made, Chandler and Arnold (1953) found 20 ignition points per acre by actual surveys of slum areas; nearly 17 of these were created by loose paper. In wholesales areas, out of 27 ignition points, approximately 24 were attributed to the same factor. In contrast, in good residential areas, only 3 ignition points per acre were found, and in downtown retail areas slightly over 4 were found. Although the methods used to collect these figures may be open to some doubt, their general indications are clear and irrefutable.

Special Materials

With regard to special fabrics, it was noted in Appendix B that heat-treated orlon has remarkable properties of resistance to thermal radiation. The transmittance of the treated orlon is still fairly high, however.

Classified paragraph on special materials has been deleted.

Classified Figure E-2 concerning smoke has been deleted.

Various research projects are in process to test the following aspects of Nimbus Cloth.

1. Effects of nets kept in front of the eyes for prolonged periods

2. Development of window screen; its stability under weathering

3. Problems presented by wind

4. Effects of thermal flashes of longer duration (from very large yield weapons)

The U.S. Army is interested in testing fabrics currently in use and in developing new fabrics which would be relatively invulnerable to intense thermal radiation--Ramsley (1959). A thorough investigation of the following five methods by which outer clothing might negate incident radiation has been sponsored by the Army at Arthur D. Little (1960).

1. Expansion to form an insulative layer--foam formation

2. Utilization of heats of reaction

3. Utilization of heats of fusion and vaporization

4. Attenuation of the incident radiation through the production of smoke and fog

5. Utilization of heats of sublimation

Classified Figure E-3 concerning
special materials has been deleted.

Table E-III

EXPOSURE OF FABRICS IN THE DRCL SOLAR FURNACE
WITH AND WITHOUT PROTECTION BY NIMBUS CLOTH

Item Protected	Conditions of Protection	Exposure Details (cal/cm^2 in 1 second)	Results: Visible	Results: Bursting Strength
Battle dress serge, All wool, 13 oz/yd^2 Khaki color	None	8	Char	Zero
	In contact with Nimbus Cloth S305	20	Very slight singe	Reduced 10%
	In contact with Nimbus Cloth S305	30	Singed pattern	Reduced by 25%
	In contact with Nimbus Cloth S306/281	30	Very slight singe	Unchanged
	In contact with Nimbus Cloth S309	30	Very slight singe	Unchanged
Cotton drill Navy blue 9 oz/yd^2	None	8	Char	Zero
	Nimbus Cloth S311 spaced 5 mm	30	Slight discoloration	Unchanged
	S311 in contact	20	Discolored but not singed	Reduced by 75%
Canadian Army summer dress fabric, nylon cotton X59-400C 5 oz/yd^2 O.D.	S311 in contact or spaced 5 mm	20	Slight singe	Reduced by 2/3
Nylon/cotton combat cloth, X60-430 8.3 oz/yd^2 O.D.	S309 in contact	30	Slight singe	Reduced by 25%

Source: Wilson and Cavanagh (Report No. 348, 1961).

Table E-IV

EXPOSURE OF FLESH OF INNER FOREARM BEHIND FABRICS AND NETS

Means of Protection	Exposure Details (cal/cm^2 in 1 second)	Results
1 layer Nimbus Cloth S305 at 5 mm spacing	10	Slight reddening of skin.
	15	Slight reddening of skin.
	20	Skin discolored. After some days slight blister appeared.
1 layer Nimbus Cloth S309 and 1 layer B.D.S.	30	No effect immediately. If hot cloth held in contact with skin for some time, slight erythema occurs.
1 layer Nimbus Cloth S309 and 1 layer cotton drill	30	No effect immediately. If hot cloth held in contact with skin for some time, slight erythema occurs.
1 layer of Nimbus Cloth S309 and 1 layer combat cloth nylon cotton X60-430	15	No effects on skin.

Source: Wilson and Cavanagh (Report No. 348, 1961).

Foam formation and smoke formation were initially considered to be the most promising protective mechanisms, based on a heat transfer criterion (Development . . . to Neutralize . . . Radiation, 1960). However, later experiments disclosed that, while smoke or fog can be exceedingly effective in attenuating intense thermal flux, the smoke particles may also ignite under certain conditions. In Quarterly Report No. 8 of A. D. Little, specific suggestions were made for further research.

Studies on the inhibitive effect of potassium bicarbonate in the ignition of cellulosic materials have recently been done by NRDL and Pacific Southwest Forest and Range Experiment Station personnel; see Broido and Martin (1961).

Eye Protection

As was described earlier, the Nimbus Cloth under development by the Canadians is also being tested as protection for the eyes. In addition, electromechanical shutters have been designed to protect the eyes from radiation (see Appendix B) (Gulley, et al., 1957). Recent research (The DYNACELL . . ., 1962) has also been concerned with the DYNACELL and focal plane concepts of phototropic systems, which should be briefly described.

In Appendix B, it was pointed out that apart from the attenuation of the atmosphere, the image of a fireball falling on the retina of an eye would have the same light intensity at all ranges from the fireball within the limits of the resolving power of the eye. This is due to the focusing action of the lens of the eye. Liquid filters are currently available which will darken in response to intense thermal radiation and have a response speed of under 30 microseconds. However, since the intensity of the thermal flux from a fireball varies inversely with range, the filters (phototropic substances) will not react at very long ranges. Hence, a lens system must be devised, similar to the lens of the eye, which places the filter at the focal plane. The image of the fireball on the lens then becomes smaller with range, but the intensity of thermal radiation per unit area remains constant (again ignoring the attenuation of the atmosphere). In addition to this sophistication, the DYNACELL concept will clear the opaque filter by purging the liquid, thereby returning the optical system to a useful function in one second or less. At present, the major disadvantages of such a system are that (1) the field of vision is restricted because the system functions as an optical device and (2) the bulkiness of the system restricts its use.

Another approach to the problem of eye protection from the initial thermal radiation has been taken by Midwest Research Institute (Development

of a System . . ., 1959). In this work, which includes a literature search on the subject, an attempt is made to develop a chemical compound which will darken in response to the thermal pulse but can be bleached rapidly by a chemical reaction.

Skin Protection

Work sponsored by the Quartermaster Research and Engineering Command in Natick, Massachusetts, has resulted in the development of a cream, designated as Cream 305X, which apparently affords satisfactory thermal protection for the skin from nuclear detonations. In 1959, Purdue University improved the adhesive properties of the cream and extended the time over which it could be worn and still remain effective (Improvement of Physical Properties of Creams . . ., 1959).

Special Screening

It was seen earlier that ordinary window glass and screens will afford significant protection from intense thermal radiation. Figures B-63 and B-64 illustrate that for a given height of burst, if the angle of elevation of the fireball is too great, a structure will be damaged by blast; if too small, the thermal radiation will not ignite interior kindling fuels. Application of this concept has evolved a special type of screen which is similar to screening material currently on the market; see Downs and Bruce (1957).

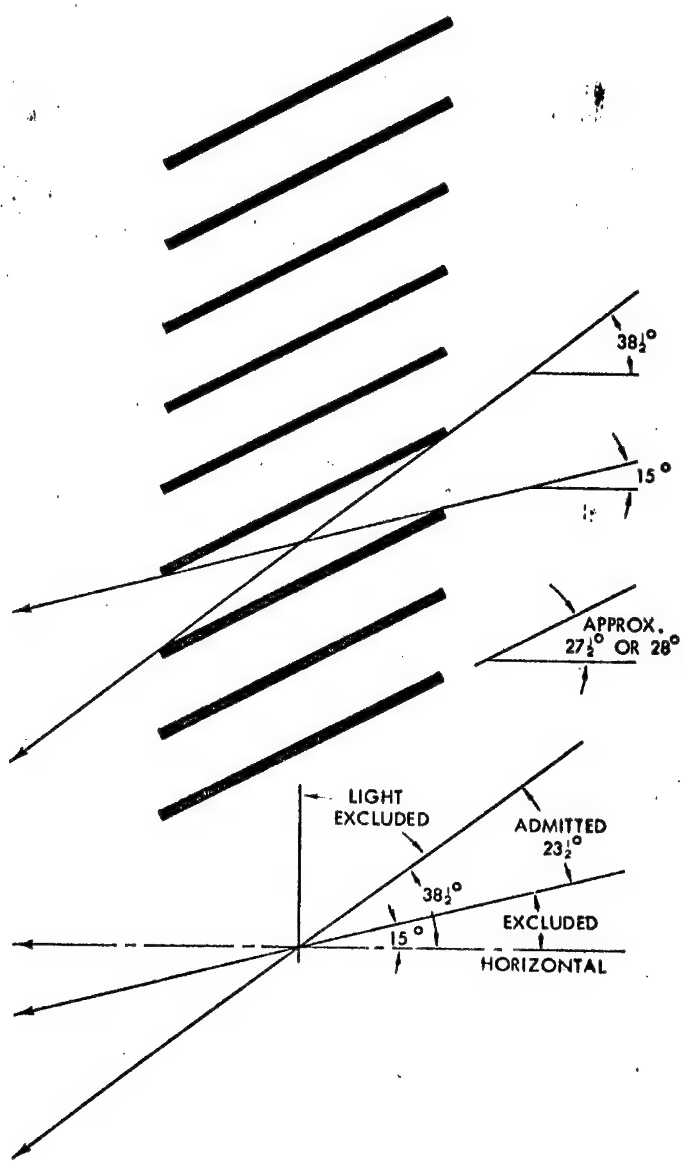
The commercially available screen is constructed of flat metal ribbons which slope downward and outward from the structure and resemble, in effect, miniature Venetian blind slats. These screens would be ineffective in reducing the fireball radiation because of angle of the slats. The proposed special window screen shown in Figure E-4, would cut out concentrated sunlight in the same manner as the commercial variety (all direct rays entering between 38° and 90° from the horizontal) and would, in addition, screen all direct radiation from 5° to 15°--the range of elevation angles considered critical by Bruce and Downs. For megaton weapons, the effectiveness of such screens would have to be re-evaluated.

Special Paints

Encouraged by the attenuation of thermal radiation by the smoke screen tests in Operation UPSHOT-KNOTHOLE and by the apparent reduction in thermal burns--due to the smoke cloud from the fabrics--experienced

Figure E-4

WINDOW BLIND DESIGNED TO EXCLUDE
NUCLEAR THERMAL RADIATION AND SUNLIGHT



SOURCE: Downs and Bruce (1957)

by clothed animals in weapons tests, the U.S. Navy undertook a program to develop and test paints which would protect against thermal radiation by smoking or foaming; see Shelberg and Martin (1958). The results of tests with thermoshielding (smoke producing) and intumescent (foam producing) paints were encouraging when compared with tests for ordinary Navy gray paint. Shelberg and Martin are quoted in part below:

> "The degree of protection varied with paint and exposure characteristics. The thermoshielding sebacic acid paint protected appreciably (7 to 18 percent) throughout a range of simulated weapon exposures extending from one of high peak irradiance and moderate yield (5 cal/cm^2/sec and 0.2 MT) to one of low peak irradiance and high yield (5 cal/cm^{2}sec and 10 MT). The explosively decrepitating thermoshielding paints, tetracene and nitrosoguanidine, protected appreciably (13 to 19 percent) when the simulated weapon pulses delivered the majority of the radiation within a few seconds, but they failed to protect when the majority was delivered during a period of many seconds. Intumescent Albi-99 protected appreciably (7 to 23 percent) when temperature rises were great enough (about 225 to 250°C) for formation of its relatively slowly produced foam blanket, but it failed completely for large, very rapid temperature rises since immediate decomposition then causes loss of the intumescent property. All paints showed appreciably sustained protection at exposures corresponding to 22 cal/cm^2/sec peak irradiance and 1-MT yield; sebacic acid paint, 14%, tetracene and nitrosoguanidine paints, 19%; Albi-99 paint, 23%."

It was concluded that even though the results above were encouraging, other paints may afford even better protection than the prototypes tested.

Countermeasures to Fires

The following paragraphs describe methods for combating incipient fires, group fires (fires in which individual structures may be aflame, but the flames have not coalesced), and mass fires (firestorms and conflagrations).

Incipient Fires

In case of nuclear attack, incipient fires would be widespread and would probably develop very rapidly. Consequently, they would probably have to be controlled at an early stage of development or not at all.

This would require extensive use of passive countermeasures or an immediate, trained response by a large proportion of the civilian population. The following paragraphs describe methods for reducing the hazards of fire spread from incipient fires.

Fire Resistant and Fire Retardant Materials and Paints

The Directory of Fire Research in the United States (1961) lists 39 activity projects which are concerned with the flammability of materials and product evaluation and development. Much research activity is also described in the Fire Research Abstracts and Reviews (1958).

Brown (1962) has estimated that 7 to 20 times as many cal/cm^2 would be required for a fire to jump a firebreak by radiant heating when structures are protected by fire retardant exterior paint. It was also found, however, that the reflectivity of practically all fire retardant paints declines approximately 80 percent to less than 10 percent after exposure to a heat flux of 10 cal/cm^2 delivered in about 2 seconds. The resultant blackening increases the total heat absorbed by the surface and decreases the effectiveness of the fire retardant. Further research is required to overcome this problem.

Confinement of Fires

A fire within a room requires at least 60 air changes for complete combustion; see Lawson (1958). Hence, many fires fail to develop if the windows and doors of rooms are closed. In World War II, the majority of German buildings burned as individual units, with little or no fire spread except in firestorm areas where the temperatures were high enough to ignite all combustibles; Bond (1946). It was estimated that approximately 30 percent of the fire damaged buildings were due to fire spread; Fire Effects of Bombing Attacks (1959). The confinement of the fires was due predominantly to the common use of firewalls between adjoining buildings and of parapets between roofs. It is stated in Fire Effects of Bombing Attacks that the cities of Germany were less susceptible to firestorms and conflagration because of the lower combustibility of structures than would be cities of similar size in the United States. The cities of Japan, on the other hand, because of building density and combustibility of structures were more susceptible to conflagration than those of this country. As part of its fire research program, the National Bureau of Standards is studying the confinement of fires. The following topics are included in its studies: burning behavior of cribs; confined fires and development of models; and structure requirements to keep fire spread within a single room of a building.

Fire Extinguishers and Fire Inhibiting Chemicals

Research is active and continuing on attempts to find new agents and methods of extinguishing and preventing fires. (The Fire Directory lists 23 active projects.) There are three physical mechanisms of extinguishment of fires (see Friedman and Levy, 1959): separating the fuel from the oxidant (smothering), removing the flame from unburned gases suddenly (e.g., blowing out a match or extinguishing an oil fire by blasting), and cooling. In addition to the above, some chemical mechanisms for extinguishing fire offer major advances based on the rapidity of certain chemical reactions. The reactions of the chemical compounds are not well understood; a review of recent progress in the field is given in Friedman and Levy.

It should be pointed out, however, that in fires started by earthquakes in Japan, fire extinguishers were often unusable because they had been shaken from their stands and had discharged or were buried in the wreckage; see Brown (1962). Such operational problems would have to be considered in the case of nuclear detonation and its accompanying blast wave.

Improved Automatic Sprinkler Systems

Automatic sprinkler systems appear to be very effective in stopping incipient fires but are subject to two severe limitations in wartime. The first is their vulnerability to blast damage, and the second is the loss of water supply or pressure which could occur under conditions of widespread fires.

During World War II, very few German and Japanese buildings were equipped with automatic sprinkler systems. In Hamburg, for example, only two automatic sprinkler systems were observed. However, it appeared that the buildings so protected benefited considerably since one portion of the buildings so equipped suffered very little fire damage to either structure or contents; see Bond (1946). In Japan, only 5 automatic sprinkler systems were noted by fire protection engineers; three were in undamaged areas and two had been through serious fires. Both of the latter failed due to lack of water, Bond (1946).

In England and northern Ireland, sprinklers were markedly effective in extinguishing fires started by incendiary bombs. Of 250 such fires in buildings equipped with sprinklers, 77 percent were successfully extinguished or effectively controlled, and 5 percent were held in check by the sprinklers until additional assistance could be obtained. Of the

18 percent failures, approximately two-thirds were due to a complete breakdown of water supply and the remaining one-third to the heavy drain on the normal water supply resulting from a large number of simultaneous fires in the area involved. In attacks where high explosives were used, only about 40 percent of the sprinkler systems remained intact and effective for fire protection; see Bomb Damage Analysis.

Improved sprinkler systems could probably be designed to overcome at least one of the problems discussed above--namely, the problem of lack of water. King (1961), for example, describes an improved sprinkler system with a 1,000-gallon water supply component. Pressure is furnished by three high-pressure nitrogen tanks which are automatically cut into the system if the pressure from the city water supply becomes low. The flame detector in this system reacts especially fast to ultraviolet radiation of flames but is not affected by sunlight, infrared, ordinary incandescent and fluorescent light, or cosmic radiation. This detector maintains a solenoid valve in an open position only as long as flames are present. The sprinkler heads are specially designed for quick action. A highly effective additive, Dow ET 460-4, is introduced into the water to decrease the extinguishing time. This additive has been effective in decreasing extinguishing time from almost nine minutes (for water alone) to slightly over two minutes.

Group Fires

Group fires are fires in which many individual structures may be afire, but the flames have not coalesced. Some of the methods which may be used to prevent group fires from spreading and developing into full-fledged conflagrations or firestorms are given in the following paragraphs.

Participation of Professional Fire Fighting Units

Professional fire fighters would probably be most effective during this stage of fire development. The incipient stage of the fires would probably be over in less than one-half hour--too short a time for professional fire fighters to be effectively dispersed. In mass fires, conventional fire fighting methods might not be too effective. In Hiroshima, for example, the public fire department and rescue units played a minor role in extinguishing the fires since 80 percent of the firemen on duty had been killed or critically injured, 60 percent of the public fire stations were totally damaged, and 68 percent of the fire trucks were

destroyed. As a result, only 16 pieces of fire equipment were available; see Fire Effects of Bombing Attacks. Direct damage to the fire department in the Nagasaki attack was much less than that at Hiroshima.

Bond (1955) and Fire and the Air War (Bond, 1946) have reviewed the action of fire fighters in both allied and axis countries during World War II. Davis (1959) and others have described in detail the control of forest fires by fire fighting units. Hishida (1952) has presented a fairly sophisticated operations analysis study of combating fires; the approach is similar to that used in military war games. Various parameters are employed, including power of the fire defense, rates of advance of the fire front, and the like. The method suggests that gaming might be a useful training tool for fire fighting forces that are expected to control fires over extensive areas. This approach was, in fact, recommended in the Woods Hole Study, A Study of Fire Problems, 1962, "The program . . . should include . . . development of player-participation games for the training of fire-fighting personnel, for the investigation of fire-fighting techniques, and for the planning of interagency cooperation in fire-suppression activities."

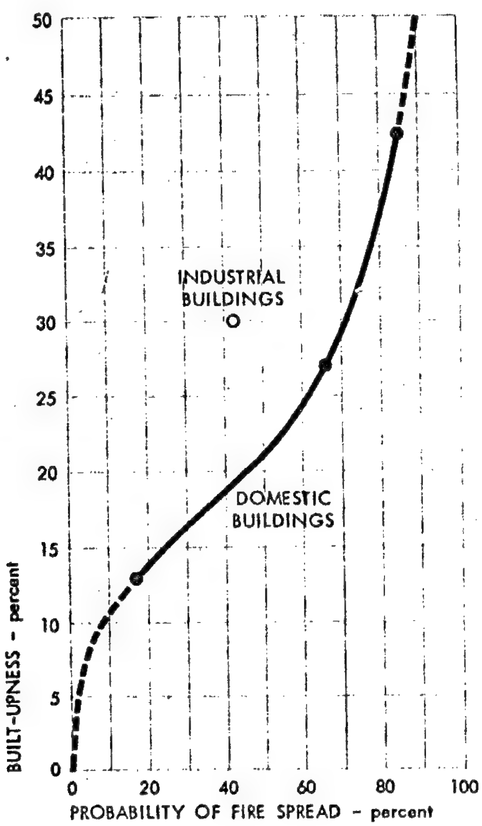
Several new pieces of equipment and new fire fighting techniques have been tested for their effectiveness in fighting widespread fires (Christian, 1958). The use of helicopters to place hose and pump equipment as an emergency fire fighting task force operation was found to be feasible, provided certain refinements of equipment are accomplished. New quick-coupling tubing systems for rapidly constructing emergency water-supply lines were acceptable; however, the concept of convection water-fog generation for controlling large unconfined fires requires further development. It was found that an expendable aluminized-paper fire fighter's ensemble could be used for protection against thermal radiation of large fires although further development is required to improve durability of the garment.

Increased Strictness of Building Codes

Fire will spread between buildings by radiation, convection, or firebrands. Radiation, the primary means of transfer in urban areas, can be controlled by either a space separation or an imperforate barrier between the source of the fire and adjacent combustible material. As mentioned before, firewalls were very effective in limiting fire spread in World War II, except when outflanked or fires started on both sides. Firebreaks and low building densities also were effective in stopping fire spread. Figures E-5 and E-6 show the probability of fire spread as a function of the density of buildings (built-upness) and of exposure distances derived from the Japanese experience in World War II. Figure E-7

Figure E-5

PROBABILITY OF FIRE SPREAD IN VARIOUS AMOUNTS OF BUILT-UPNESS



SOURCE: Bond (1946)

Figure E-6

PROBABILITY OF FIRE SPREAD ACROSS VARIOUS EXPOSURE DISTANCES

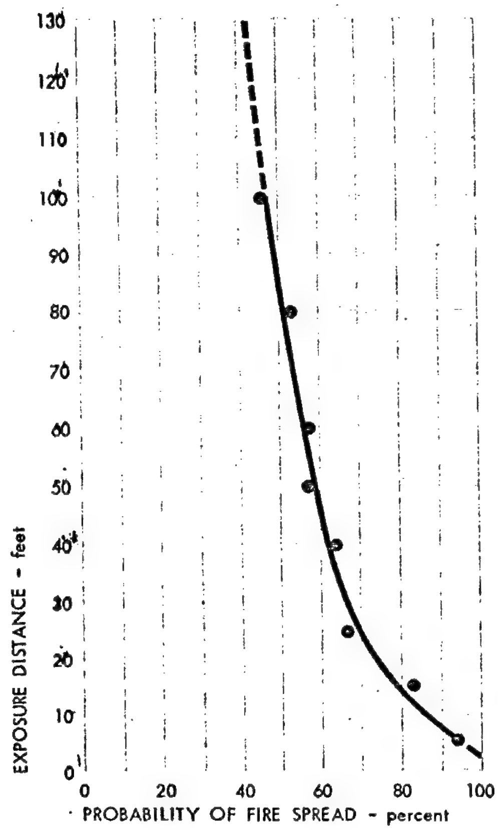
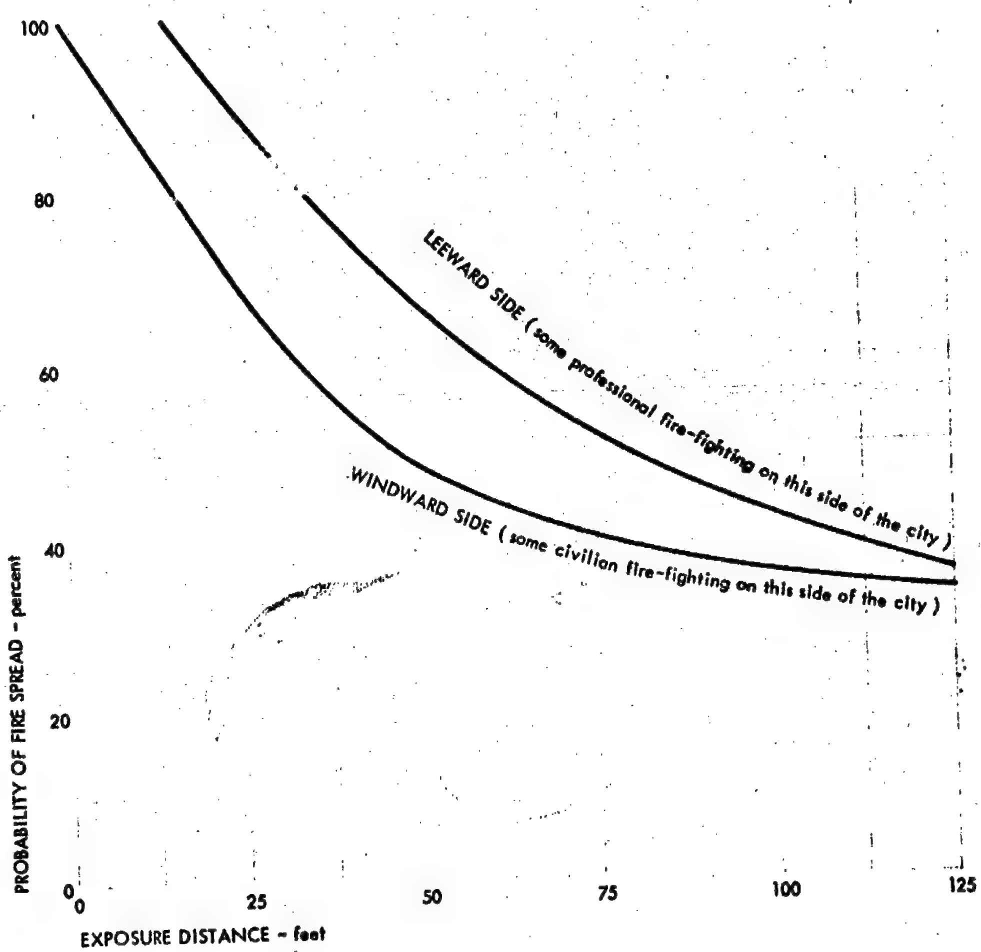


Figure E-7

RELATIONSHIP BETWEEN FIRE SPREAD, WITH AND AGAINST A LIGHT BREEZE, AND THE PROBABILITY OF FIRE SPREAD ACROSS OPEN SPACES



SOURCE: Bond (1946)

gives similar data except that the effect of wind is included. Actually, in Japan, many of the constructed firebreaks were ineffectual not because of their width, but because the widest firebreaks were usually in the center of the city where they were easily flanked by bombs on both sides; see Fire Effects of Bombing Attacks.

Classified paragraph on fire spread
has been deleted.

Thomas (1960) has developed an analytic method to determine the space separation between buildings required to prevent fire spread by radiation. The method can be applied in the construction of new buildings by either varying the location of new buildings in relation to the property boundaries or adjusting the designs--that is the area and arrangement of windows and the nature of the external walls. This method would appear to be valid in the United States.

Experience in the Bel Air fire (Wilson, 1962) led to many conclusions and recommended changes in city ordnances. It was found, for example, that attic vents or louvers, even when covered with mesh, created dangerous drafts through which sparks and firebrands could enter. Overhanging eaves, porches, and houses formed hoods to trap heat sweeping up from brush fires; large glass areas were vulnerable to heat caused by fire and when shattered would allow heat, smoke, sparks, and fire to enter.*

The strongest recommendation resulting from the Bel Air fire was that wood shingles and shakes should not be permitted on new construction. Roof sprinklers proved ineffective during this fire; even when the water supply was ample and accessible, high winds blew the water away from the roofs.

* In respect to windows in industrial or commercial areas, Earp (1953) suggests that the bricking up of windows, although unpopular, would be extremely effective in reducing radiation between buildings and, at the same time, would prevent interior fires starting from the thermal flash.

Elimination of External Kindling Fuel

Wilson (1962) recommends that an area of 30 feet around a structure should be maintained free of vegetation and that in the area between 30 and 100 feet trees and shrubbery should be low in height.

The problem of reducing the fire hazard of vegetation through chemicals has been studied by the U.S. Forest Service, the Georgia Forestry Commission in a joint project with the Southern Forest Fire Laboratory, and several U.S. chemical firms (Test Data, U.S. Forest Service). The programs have resulted in the development of chemical applications which are absorbed by vegetation and serve both as a fertilizer and as a fire retardant. The process, using any one of three chemicals, is apparently effective for both uses. The following chemicals have proved successful: (1) ammonium sulfate mixed with water, a coloring agent, and colloidal clay to form a slurry; (2) diammonium phosphate combined with a masking dye; and (3) primary ammonium phosphate. Application would have to be made annually since the fire retardant effects last only a year. The chemicals are not toxic to animals, permitting the process to be used on grazing lands.

Countermeasures and Mass Fires

In Hamburg, although fire department personnel extinguished fires in 2,427 buildings and prevented extension to 635 buildings on the fringe area, their primary job was to save lives; see Fire Effects of Bombing Attacks (1959). Once a mass fire is established, modified techniques of forest fire fighting could be added to the established methods of urban fire fighting. These additional techniques would include the use of aircraft for spraying chemicals, dropping supplies, moving personnel, locating the fire front, and controlling operations. A current project of the Forest Service, Operation Firescan, is directed toward development of infrared equipment which could spot fires that are less than 1 square foot in area. Definition of fires from the air is very difficult (especially where trees hide the radiation); locating the fire edge through smoke is a serious and important problem. As an example, a recent 300-acre forest fire created convection currents 17,000 feet high and a smoke layer 1,500 feet thick. The fire front could not be located accurately within three-quarters of a mile.

Other techniques that could be used in mass fires are (1) backfiring and (2) establishing firebreaks with bulldozers or by demolition. There is considerable doubt, though, as to their advantages. Demolition of buildings to create firebreaks was seriously considered by the Germans

during World War II. However, the speed with which the fire traveled and the frequent change in direction due to the unusual air currents and radiated heat made the selection of suitable locations for demolition impossible. The German fire departments are now firmly convinced that demolition in time of mass fires of wartime proportions is not sound and causes needless destruction; see Fire Effects of Bombing Attacks.

The only methods for protecting the population from mass fires are the use of open spaces or canals, shelters, and evacuation. Since 85 percent of the population of Hamburg survived by these means (see Appendix D), they cannot be ignored.

In Hamburg, it was determined that open spaces (parks, greens, etc.) must be a minimum of 300 meters (915 feet) in diameter to protect the population from radiant heating and flying sparks. On one green 365 feet square, over 100 persons, who had sought safety in the center, were burned to death; see Earp (1953).

The waters of the existing canals in Hamburg offered fairly effective protection. Many refugees failed to reach them, however, and those who did were often burned on their heads. Subsequent to the Hamburg catastrophe, it was suggested that the Germans might build artificial canals. However, these "water lane" escape routes were never constructed because of the large amount of equipment and water required.

Earp describes in detail the shelters available in Hamburg in World War II. Two fairly common types were the bunkers and the "splinterproof buildings." The bunkers were even more elaborate than a modern, large capacity fallout shelter. They were divided into many rooms or compartments and often were multi-storied. They had their own air treatment and control facilities and were built to resist direct hits by high explosive bombs. Although there was much discomfort in these units due to overcrowding, all occupants survived the firestorm. The splinterproof buildings were built of reinforced concrete and had a capacity of as many as 500 people. They had air-locks at the entrances and presumably a self-contained ventilating system. No casualties were reported in these shelters.

Basement shelters, either public or private, were not so successful in protecting the occupants. They were often buried in hot rubble. Not only was the heat unbearable, but in the majority of cases death occurred from the inhalation of carbon monoxide.

Broido and McMasters (1960) have studied the environment in shelters with special reference to fires. Their conclusions, tempered by the fact that their experiments were on a small scale (9 and 4 acres) compared to what might occur in a firestorm, are as follows:

1. Extreme carbon monoxide concentrations are to be expected in large scale fires burning out of doors.

2. Although oxygen depletion and high carbon dioxide concentrations may also occur, their effects will be of consequence only if some steps are first taken to eliminate the carbon monoxide hazard.

3. Air temperatures in the fire may be expected to exceed 2000°F, and conventional ventilation systems, if operated during the fire, may be expected to carry into the shelter much more heat than is generated by the shelter occupants.

4. If ventilation systems are to be operated during a fire, shielding of the intake vents from radiant heat should be considered since, under certain circumstances, cool intake gases may actually be heated in passing through the vents.

5. Smoldering rubble will maintain higher temperatures and toxic gas concentrations for longer periods than the more impressive flaming phase of a large fire. In fact, it appears that if shelter vents are located so that they will not be covered by rubble, closure for more than an hour or two will seldom, if ever, be necessary. Conversely, if the vents are covered by rubble, closure for a period of days may be required.

6. Placing a home shelter vent just outside of a residence may be of little value since high concentrations of toxic gases will sometimes be found in this location.

7. Although fatal concentrations of carbon monoxide were found 5 feet from the fire--and concentrations sufficiently high to cause headaches were found 25 feet from the nearest fuel--during the Briones Burn, no significant concentrations were found outside of the burning piles during the Camp Parks Burn. What would occur in a much larger fire is impossible to predict, but a good rule to follow would seem to be: where possible, locate a shelter in a cleared area sufficiently large that the shelter will not be covered with rubble, and within that area locate the vent as far as possible from combustible materials.

A current Office of Civil Defense sponsored project undertaken by the General American Transportation Company, Chicago, is studying environmental control systems for shelters closed for a period of 24 hours. The work to date has emphasized O_2, CO_2, and toxic gases, rather than CO, temperature, and humidity. Costs have been estimated for both family and large shelters. A family shelter, for example, would require an expenditure of approximately $17 for O_2 supply, 10 cents per man hour for CO_2 control, and 25 cents for the total period for the combustion of CO. From these data, it appears that in sealed shelters, the costs of the control of the chemical balance of the air would be relatively reasonable.

In a firestorm area evacuation would be very difficult because of the intense heat and the fact that the streets act like flues for the hot gases and induced winds. Again in Hamburg, it was determined that heat, rather than poisonous gases, caused the greatest number of deaths.

Appendix F

This appendix, which describes thermal pulse shapes, is entirely classified and consequently has been deleted.

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